ESD-TDR-64-535

(FINAL REPORT)

THE RANGE OF VISUAL SEARCH

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-64-535

NOVEMBER 1964

John Volkmann
Horace H. Corbin
Nancy B. Eddy
Carol Coonley

DECISION SCIENCES LABORATORY
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

Project 7682, Task 768201

(Prepared under Contract No. AF 19 (604)-3037 by
Mt. Holyoke College, South Hadley, Massachusetts.)

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Foreword

This report deals with a long series of experiments conducted at Mount Holyoke College by members of the Psychophysical Research Unit. It could not be "complete", because an exhaustive account of the experiment would make a book; furthermore, a quite unreadable book. Instead the aim has been to produce a condensed and relatively thoughtful report, one which tries to present both the ideas that we had at the time of doing the experiment, and the ideas that we ought to have had. Science is quite as much hindsight as foresight.

The first experiments under this contract dealt with search in psychophysical cyclorama. These are reported briefly in a Vision Committee publication.[1] The remaining experiments fit together acceptably under the title, The Range of Visual Search.

This report has been put together by the undersigned as Director of PRU, with the full cooperation of his friends. Dr. Corbin prepared the appendix on the preparation of matrices. Mrs. Eddy and Miss Coonley analyzed their own extensive experiments and others. Mrs. Reese advised with the preparation of the report. Dr. Reese cooperated in important ways as chairman of the department. The contributions of individual experimenters are recognized in the text; some of these were undergraduates at Mount Holyoke College.

It is a pleasure to acknowledge the patience and cooperation of officials of the Air Force: Mr. William H. Sumby, our project monitor; Mr. C.W. Cantrell, our contract officer; Mr. Bennett Bolton, the property representative.

As always, the business office and maintenance division of Mount Holyoke College have supported our efforts; the names include Mr. Otto Kohler, Business Manager; Mr. Edward Babbitt, Comptroller; Mr. Lawrence Remillard, Assistant to the Comptroller; Mr. Earl Frank, Assistant Superintendent in charge of Operations.

John Volkmann
Director

THE RANGE OF VISUAL SEARCH

Abstract

The aim of these experiments was to study the process of visual search in its early phases. Individual human subjects searched in a projected matrix of elements for one element unlike the rest; e.g., for a triangle in a matrix otherwise composed of circles. In the method of lasting exposure, the matrix was exposed until the subject responded, and the dependent variable was the latency of the response. In the method of brief exposure, the exposure time was limited, and the dependent variables were the percentage of positive responses and the latency of the positive responses. ("Positive response" means that the subject found the desired element). Among the independent variables (or classes of them) in various experiments were the following: the total number of elements in the matrix; the type of discrimination (form, area, color); the external form and internal pattern of the stimulus array. In analyzing the results of a typical experiment, the median latency is plotted as a function of the number of elements in the stimulus array.

The graph begins at nearly zero slope, and usually shows a small discontinuity or a sigmoid transition leading to slightly higher latencies. This triangle locates the critical number (CN): the number of elements at which it occurs. The critical number varies considerably with the type of discrimination required, and with the stimulus difference between the critical and background elements. It can be determined for arrays that are irregular in external contour or internal pattern.

The critical number represents some discriminatory limit or limits; it may be a limit of area rather than of number. In dealing with large matrices, the subject apparently searches rapidly in a region around the fixation point (the initial sub-matrix). By definition, this has an area equal to that covered by the critical number in the matrix. The interpretation of the critical number and the initial sub-matrix is partly in terms of saccadic eye movements, though none have been photographed as yet.

The region of fast search may have at least an approximate shape. One experiment, using the method of brief exposures, indicated the shape to be ovaloid, with most of its area lying above the fixation point.

This Technical Report has been reviewed and is approved.

FOR THE COMMANDER

Donald W. Connolly

DONALD W. CONNOLLY
Chief, Display Division
Decision Sciences Laboratory

for James S. Dunn

ROY MORGAN
Colonel, USAF
Director, Decision Sciences Laboratory

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INTRODUCTION

A. Historical Setting

The term search seems to be a modern equivalent of the older term active attention. As opposed to the passive variety, active attention meant that the human subject was set to receive a particular stimulus, out of many stimuli that might be forthcoming. Passive attention designated the other common psychological situation in which an unawaited stimulus "attracted" the attention of the subject. The classical conditions of attention such as novelty, movement, striking quality, etc. are conditions of passive attention. The discovery of the Aufgabe (consciousness of set) helped to clarify the relation between the two kinds of attention: active attention is characterized by an Aufgabe, passive attention by the interruption of a previously existing Aufgabe.

The first important model for attention was Wundt's two-level model. Part of the contents of consciousness lay in the focus of attention, Wundt said; these contents were not only perceived but apperceived. Other contents lay in the margin of consciousness, being perceived but not apperceived. Some of Wundt's fellow-psychologists thought that more than two levels of clearness would be required to describe human consciousness.

Next came the views of Wundt's pupil, Titchener. As a conscientious structural psychologist, Titchener sought an account of attention in terms of content alone. Apperception was too much like an act, and it did not seem necessary to concede the important area of attention to the opposing school of act psychology. So Titchener proposed a fifth attribute of sensation, attensity, in addition to the usually recognized attributes: quality, intensity, extensity and protensity (duration). Attensity is sensory clearness; this is different from distinctness or sharpness of contour.

A doctrine of sensory clearness raised questions concerning other established facts of attention. How much conscious content could be highly or maximally clear at one psychological time? The answer seemed to lie in the classical experiment on

the range of attention. If one shows tachistoscopically about 10 capital consonants, the subject can report correctly on the average about 3.5 of them. What about the consonants that the subject does not report? We can hardly assert that they were as clear as the ones that he did report. Many psychologists have argued in this way.

Yet this is not the way that the pupils of Titchener took. Dallenbach drew the distinction between sensory clearness and cognitive clearness. According to him, the experiments on range dealt only with cognitive clearness and told us little about the clearness of the subject's sensations. To shed light on that important topic, Gill and Dallenbach devised an ingenious set of operations.[2] They varied the number of elements in the tachistoscopic field and instructed their subjects to report whether or not all of the elements were equally clear. They obtained measures of equal clearness as high as 18 elements, considerably beyond the range of attention as usually measured.

There is a basic difficulty with these operations, nevertheless. They offer no assurance that any particular element in the stimulus array was as clear as the rest. Indeed, what would happen if the subject had not seen a particular element at all? He might still report the others as being equally clear. Apparently what is required is some kind of local check upon the discrimination of the stimulus elements, even if we do not require the subject to reproduce these elements.

Turning now to the range of attention experiment: There are no simple answers in its method or its results. Some of the complications follow. a) The range is - for the most part - a statistical affair; Fernberger chose it as an example for the application of the method of constant stimuli.[3] The range is then defined as a limen, i.e. as the number of elements that is reported correctly 50% of the time. So we are not dealing with a single whole-number or anything like it. b) the range exhibits a marked practice-effect. c) The range varies with the particular discrimination that the subject is required to make. For example, it may be 3.5 when the subject must reproduce the capital letters that he has seen, but it

is 6 or more when he must report correctly only the total number of the letters exposed (not their identity). The range represents a kind of informational limit, but it is not yet clear what kind. d) The frequently-mentioned "magic number six" refers mainly to the discrimination of the number of stimulus objects, yet this would seem to be a special case. The most relevant research comes from our own laboratory at Mount Holyoke: our measurements marked off a stimulus region 1-6 in which the number of elements is reported rapidly, confidently, and correctly. The corresponding discriminatory process is called subitizing. There is as yet no clear evidence that subitizing characterizes any discrimination other than that of stimulus-number. e) The most obvious difficulty with the range of attention experiment is its involvement with memory. As any subject in the experiment can testify, by the time he has written down 3 or 4 consonants he has lost about as many more. The memory after-image of the tachistoscopic field fades very rapidly. The range might therefore be a limit of short-time memory, having little to do with differential clearness in a preceding visual scene.

The last-mentioned difficulty will explain why Dallenbach expected to find a limiting number of clear elements higher than the usual range of attention. There is another possible reason also; it lies in the phenomenology of everyday life. If you take a good look - but not a long look - at the visual scene that confronts you in a crowded room, you will conclude that a very large number of separate features compose this scene. Many of them seem about equally clear. A fraction of a second later, when we close our eyes, almost all of this has gone; it was there all right, but nothing adequate can be done to reproduce it or describe it. Of the hundreds or thousands of presumably separate details, only a handful can be sketched or written down.

The experimental psychologist is of course not satisfied with this phenomenology. It is for him only the beginnings of a scientific venture. His most characteristic task is, as usual, to devise a set of operations that will substitute measurements for talk; operations that will do justice to his scientific material.

What are the requirements for a method that might do justice to the process of search in a rich visual scene?

B. Requirements of a Method

a. The first requirement is to avoid the limits of short-term memory. Our measure cannot be the number of elements reproduced or recognized following a brief exposure.

b. The next requirement is to cover a wide variety of conditions of search. We want to produce within the same experimental setting the situation in which a sought-for stimulus stands out like a sore thumb, and the situation in which it is lost like a needle in a haystack. (Strangely enough, this is easy to do.)

c. The subject will be searching among a number of discrete stimulus elements. The conditions of his search must impose on him maximum uncertainty with respect to the sought-for element: it may be any one of the array of elements, or none of them.

d. To guard against non-valid positive responses, there must be provided a way of checking each positive response against some discriminable property of the stimulus field. Yet the amount of information required in the check must be minimal, so that the check does not limit the primary performance of search.

e. Specifically, we wish to measure the number of separate stimulus elements that the subject can process for a particular discrimination within a minimal time.

Naturally this list of requirements was not drawn up de novo at the beginning of the research; some of the requirements represent our hard-won hindsights. Even these are subject to revision. For example, it might turn out that the sheer number of stimulus elements imposes no limit on the subjects' discrimination, and that whatever limits there are must be stated in some other terms. Yet the foregoing list is a good introduction to our method.

II. Development of a Method

A. Some Basic Operations

Our ideas about method, such as they were, drew inspiration from friendly sources. One source was Dr. Herbert M. Jenkins, now of the Bell Telephone Laboratories. We heard by word of mouth of an ingenious device that Jenkins had concocted. He was interested in the "give-up" time of subjects on a dull, protracted task, and found his experimental material in a large piece of perforated acoustic panel. The holes in the panel form a regular, rectangular matrix of thousands of elements. The subjects were told that one hole - only one - had been plugged up and that they were to search for that hole.

Another source was an experiment on search by Anderson and Green.[4] They presented fields of randomly-arranged three-digit numbers, and required the subjects to search for a particular number.

The basic idea, then, is to present a rectangular matrix of stimulus elements that are all alike except one. Think, for example, of a matrix of small, solid black circles in which one equilateral triangle has been substituted for a circle. The subject searches for that one, and we measure the time between the exposure of the matrix and the onset of his locating response. The number of elements in the matrix is varied systematically over a wide range. When the number of elements is small, the initial element (the triangle) stands out like a sore thumb; when the number is large (in the thousands) the triangle is lost like a needle in a haystack. So much for requirement b) above. We are asking the subject to spot the presence of a single element, the triangle; if he can remember for a few seconds about where one triangle was, we should not be encountering any limit of short-term memory, requirement a). From his point of view, the triangle may replace any of the circles in a matrix; this was at least a beginning in satisfying requirement c). We can provide some check on the subject's positive responses by requiring him to locate approximately the triangle in the matrix (requirement d). Precise location would surely defeat the method, but if the subject can locate the

triangle very approximately, we may assume that a triangle has indeed appeared somewhere in the matrix, and that it was correlated with the stimulus-triangle.

B. An Early Form of the Method

An early form of this method was developed and thoroughly tried out by Miss Jacqueline Carter of our staff; the method and the results appear in her master's thesis.[5] (Parenthetically, the thesis was of much more than ordinary interest).

Small, solid black circles and one solid black equilateral triangle made up the stimulus matrix. The elements were arranged in regular rows and columns. The circles were all the same size; as presented on the screen, they were 0.53 inches in diameter and placed 1.12 inches apart on centers, horizontally and vertically. The triangle was chosen to be about the same subjective size as the circles; its altitude was 0.5 in. and size length 0.56 in. The triangle always rested on a base. A sample matrix is reproduced in Fig. 1. The stimulus matrices were square in external shape, except for the 4 smallest matrices; these formed rectangles 2 x 1, 3 x 1, 3 x 2, and 4 x 3 elements respectively. After much deliberation we chose an IBM electric typewriter, together with special type, ribbon and paper, to make the matrices. Because of the necessity of randomizing the position of the triangle, a method of printing or lithographing seemed much too expensive. The special circular type measured 0.085 inches in diameter; the altitude of the triangular type was 0.08 in. The paper, as recommended by the local IBM office, was Linweave Coldstream Bond, rag-content 24, 11 x 11 in. The ribbon was IBM carbon #5550-1. The resulting product seemed sharp in outline, precisely spaced and high in contrast. The typing was laborious and demanding. The characters were placed one typewriter space apart horizontally, and double-spaced vertically. This produced uniform spacing of the matrix as described above.

To project the original typed matrices we used a Beseler Vulyte-2 opaque projector, Model #P52/33 (See Fig. 2). The projected image appeared on a seamless

Fig. 1

Showing a sample matrix from Carter's experiment. The S searches for the triangle in the matrix of circles. There are 484 elements in this matrix.

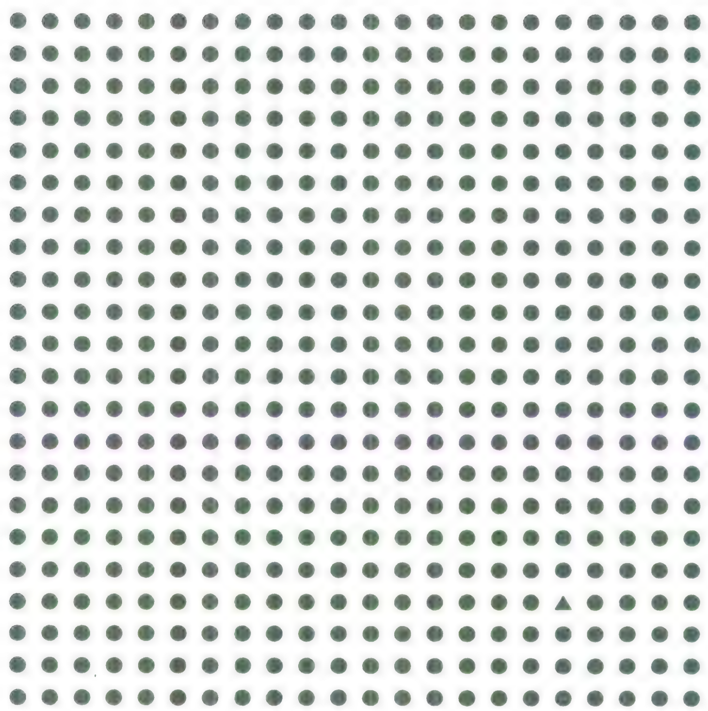


Fig. 2

Showing an overall view of Carter's experimental situation. From left to right, the timing apparatus, opaque projector, experimenter, projection-screen with a large matrix.

matte-finish screen 5 ft. 7 in. square placed 9 ft. 6 inches in front of the subject. The center of the screen was 4 ft. 10 in. from the floor. The luminance of the screen was read on a Macbeth illuminometer with a blank piece of the special stimulus paper exposed in the projector; the average reading was 0.928 footlamberts. The room was otherwise blacked out, and only very dimly lit.

Like most large projection fields, this one offered some difficulties. We wanted a large-diameter, electrically operated shutter. A commercially-obtained one proved to be worthless, and we then made one out of two halves of an Aubert diaphragm; each half was mounted on a lever, and operated by a heavy solenoid. (A later version proved to be better than this one). There were some shadows near the top and bottom edges of the screen, due apparently to the optics of the projector. It was not possible to get both the middle of the image and its edges in sharpest focus; some compromise was necessary. Fortunately these troubles proved to be minor, and the system gave us generally good results.

The subject awaited the exposure with her right index finger cocked and ready to point; when she saw the triangle (or other critical element) she pointed at it as fast as possible. In pointing, her finger struck a piece of plate glass 14 in. square located 13 inches in front of her eyes; the top of the glass was tilted 35 degrees toward the subject. Fig. 3 shows this arrangement. The plate glass bore a small contact-microphone which fed a 12-watt audio amplifier and this in turn, fed a Sigma sensitive rectifier relay. Briefly, the reaction-time that was started with the exposure of the matrix was stopped when the subject's finger struck the glass.

The same pointing reaction also provided a check on the validity of the subject's response. The index finger bore a miniature projector which could cast a diffuse spot on the projection screen, through the plate glass. When the finger struck the glass, the matrix vanished, the screen became dark, and the subject then quickly pointed to the region of the screen where the triangle had

Fig. 3

Showing the S and the response system in Carter's experiment. From left to right, the glass plate and contact microphone, S's finger and finger-lamp, the S, dividing screen and projector.

just been. The experimenter looked over the apparatus and checked this location against the stimulus location.

The block diagram of Fig. 4 helps to explain the sequence of events in experimentation. The solid lines in the upper half of the diagram represent the events in starting the exposure and timing it; the dotted lines in the lower half represent the events in stopping it and in the checking process.

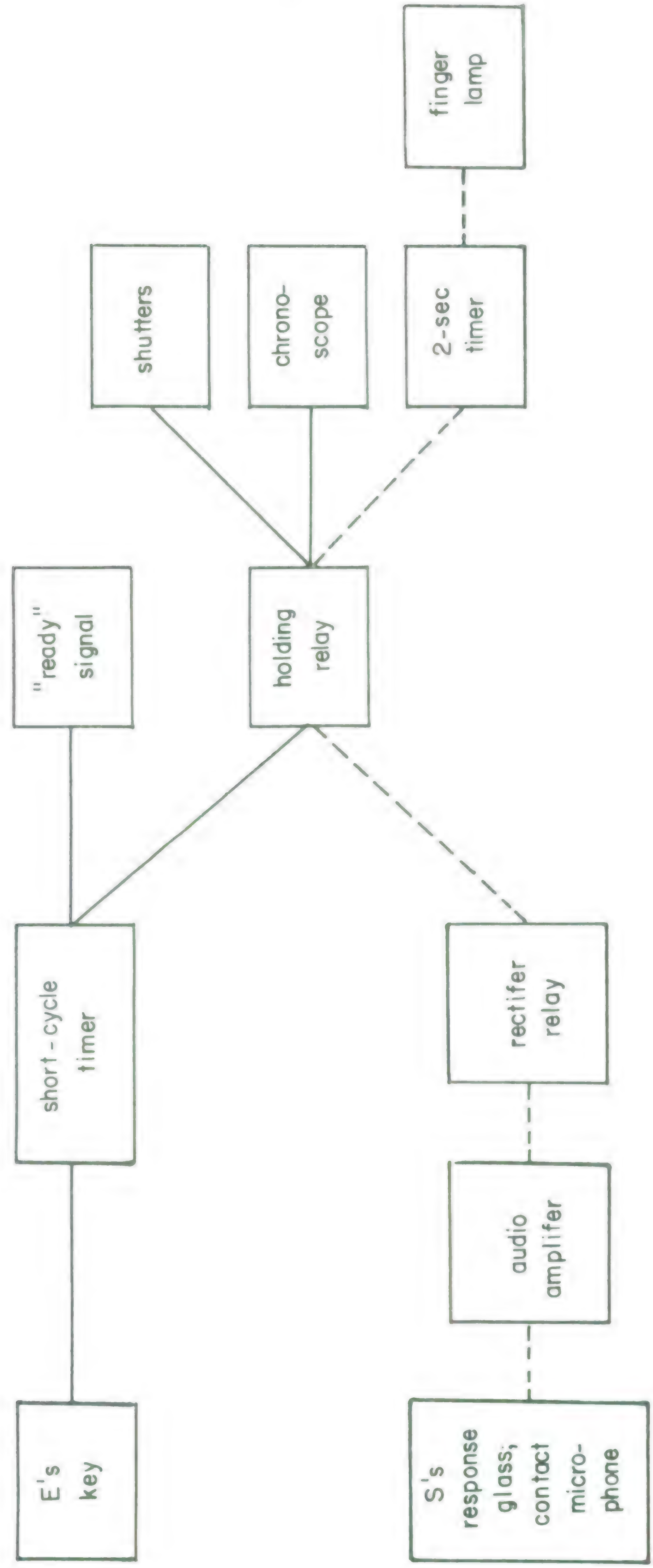
The sequence of events was the following: the subject looked at the screen and raised her hand, index finger, and finger lamp. The experimenter closed a telegraph key, which started a short-cycle synchronous timer. The timer sounded a chime as a ready signal, and the subject then fixated the subjective center of the square projection screen; this was a feature emphasized in the instructions. One and one-half seconds later the timer closed a holding relay that opened the projection shutters and simultaneously started the chronoscope.

When the subject saw the triangle she immediately pointed at it, as if trying to shoot it down. The impact of the finger on the glass jarred the microphone and the resulting amplified vibratory pulse opened the rectifier relay. This opened the holding relay; the chronoscope stopped and the shutters closed. The finger lamp came on; the subject pointed and the experimenter checked the pointing. After two seconds of being on, the finger lamp went off. The synchronous timer stopped; the experimenter read the chronoscope, reset it, and replaced the stimulus sheet with the next one; the system was ready for the next exposure.

The stimulus matrices were of constant density: as the number of elements in the matrix grew, so did the area covered by the matrix. The number of elements in the 32 basic matrices follows: 2, 3, 4, 6, 9, 12, 16, 25, 36, 49, 64, 81, 100, 144, 196, 256, 324, 400, 484, 576, 729, 900, 1089, 1296, 1521, 1764, 2025, 2304, 2601, 2916, 3249, 3600. The largest matrix, of 3600 elements, filled the projection screen almost completely. Some of the smaller matrices were rectangular; all of the rest were square.

Fig. 4

Showing a block diagram of Carter's apparatus. The upper blocks, connected by solid lines, initiate the exposure and timing. The lower blocks, connected by dotted lines, terminate them.


E's key
short-cycle timer
"ready" signal
holding relay
shutters
chrono-scope
2-sec timer
finger lamp
S's response glass; contact micro-phone
audio amplifer
rectifer relay

For all matrices of less than 12 elements, the triangle appeared in each position in the matrix. For each matrix of 12 elements and larger, the triangle appeared in one of ten positions in the matrix, with these positions being chosen according to a sampling scheme. The scheme was to divide the area of the matrix into 9 equal (or nearly equal) squares, and to choose one position at random from each square. To these 9 positions was added a 10th in the precise center of the matrix (or one of the 4 positions closest to the center). Each stimulus sheet was shown to each S 10 times, so that there were 100 observations per number-of-elements per S. There were in all 294 different matrices, and these appeared in random order. Miss Carter prepared 10 different randomizations of the sheets, and showed all 10 to each S, following a few practice trials. Six women of college age served as S's. Their vision met the requirements of the Keystone Visual Survey, and none wore glasses.

C. A Methodological Trap

It is ironic that, having begun with a fairly good method, we should change to a worse one. Our experiment measures a discriminatory reaction-time in a complicated stimulus situation. Experimental psychologists have known for a long while that reaction-time experiments are full of well-disguised traps; we fell into one. Let us see why.

In Carter's experiment the S was often surprized by seeing a large matrix when (for any reason at all) she was expecting a small one, or conversely. The "surprize" might affect the reaction-time; this seemed to be an unnecessary complication. To avoid it, in one experiment we first presented a matrix (without a critical element) as a sample for size, and then presented a block of six matrices of the <u>same</u> size. The S was fully instructed about this procedure, and had no uncertainty regarding the areal size or shape of the matrices to which she would be responding. (The uncertainty regarding the location of the critical symbol within a matrix of a given size was of course maintained. At the time, this seemed to be the main requirement). In another experiment, we first presented an

empty square border to indicate the area to be covered by the forthcoming short block of matrices; the purpose was the same, to remove the S's uncertainty regarding matrix area.

The results of these experiments were in many ways like Carter's results, especially with medium and large matrices. For many purposes, the results are still useful. But a pair of vigilant experimenters (Mrs. Nancy Eddy and Miss Carol Coonley) detected trouble in the form of some improbably short reaction times ("false reactions", in effect.) They located the trouble as follows: with low numbers-of-elements (small matrices) the S could follow her instructions for speed and make a very rapid response as soon as the exposure field came on, or started to come on. The field promptly turned off, but in the short time before it did so she could dependably locate the critical element. She was making a kind of two-phase response, where only one phase was desired or recorded. With medium and large matrices, there was naturally no opportunity for this behavior. The critical element would usually take so long to find that the subject could not respond before actually finding it.

The remedy for the trouble was two-fold, and was promptly undertaken. In the first place, we returned to the complete randomization of number-of-elements, to restore full uncertainty regarding this variable. Any effect of S's "surprize" must apparently be tolerated. In the second place, we used occasional blank stimuli, consisting of matrices without a critical element. The S was told that these would come from time to time, and was instructed not to respond to them. The effect was most probably to raise her confidence-criterion for responding (related to her "operating characteristic" in the language of informational models), and to lengthen slightly her average reaction-time.

D. A Later Form of the Method

Research people usually have their eyes on new findings, new implications or new models. They can also contribute substantially by developing new methods. Let us see how a more recent form of our method compares with the early form

described above, the method used by Miss Carter.

The discrimination is the same: the S still searches for a solid black triangle in a regular matrix of solid black circles. The opaque projector, the screen, the viewing distance, the dimensions of the elements and the spacings on the paper and on the screen, - these are all the same. The projection lamp is changed after 25 hours of service to maintain its light output and the brightness of the screen.

Several of the apparatus-components are different; for one, the shutter. It consists of 4 aluminum-alloy vanes arranged like the leaves of a Venetian blind, each one turned nearly 90° by a rotary solenoid. Actuating the solenoids makes the vanes rotate rapidly and opens the lens of the opaque projector; when the solenoids are turned off, the vanes rapidly reclose. The vanes, when opened, do not show in the projection field because they lie close to the projector lens. The shutter is noisy, somewhat crude, and occasionally requires mechanical repair. In spite of these drawbacks, it has produced thousands of exposures successfully. We hope in the near future to measure its performance in detail as a function of time, using a newly-acquired Grass recording camera. Perhaps it will then be replaced with a still newer model: lighter, faster, and less noisy.

The S's mode of response can be seen in Fig. 5. There is no glass plate. The S looks at the screen with her right arm supported in an adjustable padded rest. To her right index finger is taped a miniature spot projector (a considerably improved version). The projector goes back into a shallow plastic V-shaped piece, where a large silver contact on the projector closes with a similar stationary contact. Only a light holding-pressure of the finger is required to keep the contacts closed. The switch is actually an electronic one; home-made but effective.

In this improved method, the S sees a small, dim fixation mark, shaped like a +, and projected in the center of the screen. The exposure of the matrix (composed of black elements on white) washes the mark out completely. Immediately

Fig. 5

Showing the S and response system in the improved method. From left to right, the improved spot-projector attached to S's finger, the V-shaped recess and contacts, the arm-rest and S.

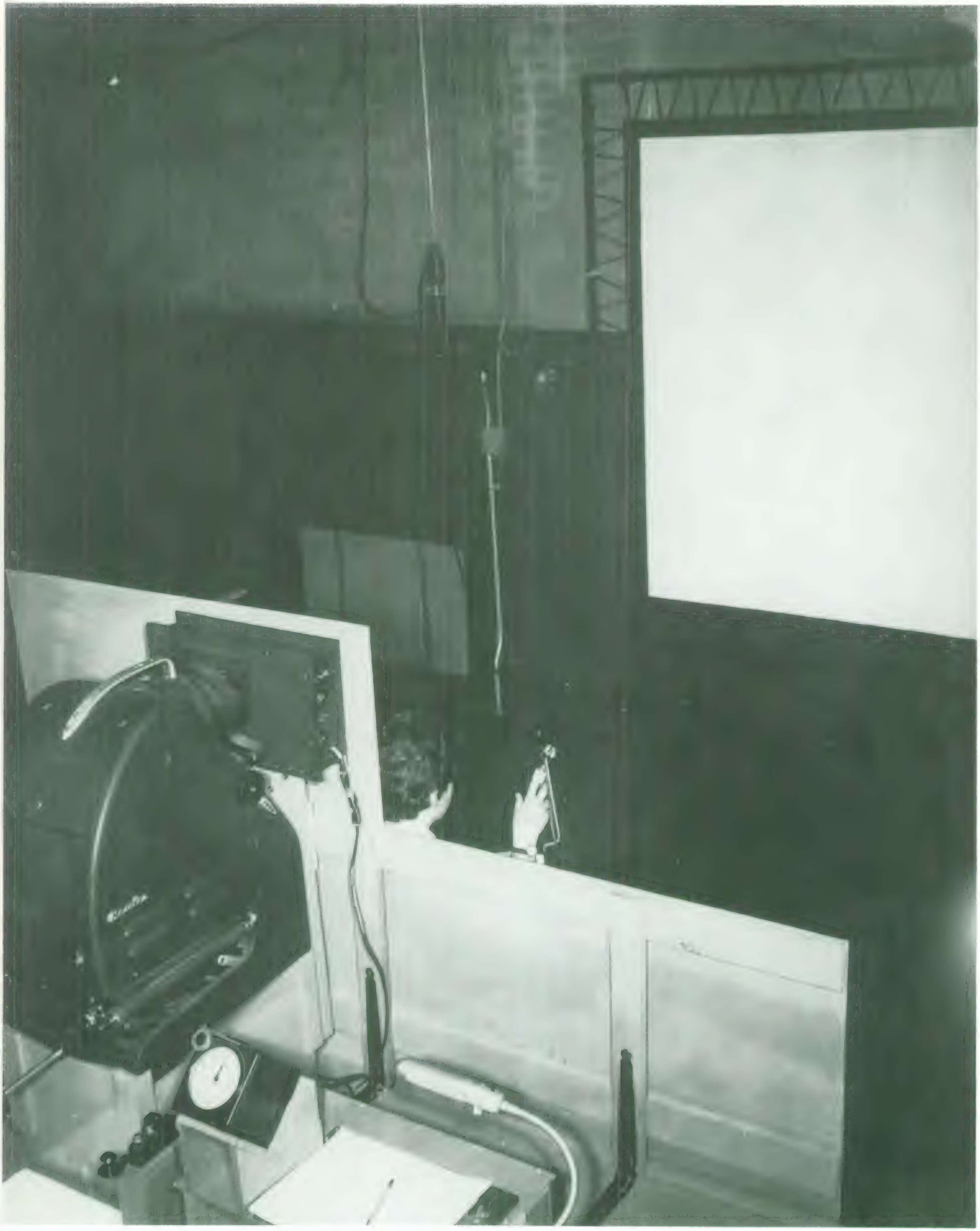
following the response and the end of the exposure an erasing field is projected on the whole screen for 2 sec., during which time the S makes her locating response. The erasing field consists of a jiggling marblized pattern photographed from the inside cover of an old copy-book, and projected from behind the E over the main apparatus. We have used the erasing field to fend off the possible cumulative effects of repeated stimulation with the projected matrices. The experiment grinds on, with several hundred such stimulations in an hour; quite possibly one (undesirable) effect of this is to render the individual stimulations less independent of one another; in effect, to make each matrix resemble too much the preceding ones. But this is all speculative, and a genuine improvement of method must await some experimental evidence on the need for erasing, and on the effects of an erasing stimulus.

To turn from component processes to the sequence of events: the sequence begins with E pressing a key to start a short-cycle timer. The timer sounds a chime as a ready signal; fixates the little + in the center of the screen and moves the finger-projector back into the V-shaped plastic piece. One and one-half sec. after the chime, the shutter opens, the chronoscope starts, and the S "searches". When she responds, she snaps her hand and her forefinger forward; the exposure field goes out, the chronoscope stops, the finger-projector comes on, the erasing field comes on. The S points to the approximate place where the critical element was, and E checks the location. The erasing field goes off; the fixation mark appears; E records the time, resets the chronoscope, replaces the stimulus sheet in the projector with the next one, and the cycle begins again. Fig. 6 presents an overall view of the apparatus; from left to right, we see E's post, the projector, the shutter and dividing screen, S and her finger-projector, and the projection screen. The timing apparatus, power supplies, and the projectors for the fixation mark and the erasing stimulus do not show in this photograph.

Whereas Miss Carter used square matrices, some later experiments have used

Fig. 6

Showing an overall view of the apparatus used in the improved method. From left to right, opaque projector, starting key and chronoscope at E's post, rotating vane shutter, S and spot-projector, projection screen. The timing apparatus, fixation-mark projector and erasing-stimulus projector do not show in this view.



rectangular ones, with a height-to-width ratio of about 1/2. The whole subject of matrix shape will be examined in later sections of this report.

As specified in the preceding section, there were matrices without a critical element, to which S was instructed not to respond. Also, the matrices of various sizes appeared in a random order, as determined with the aid of a random number table. The placement of critical elements within the matrices has followed various sampling schemes, dependent upon the purpose of the experiment and the subsequent analysis of its data. It is useful to include the element lying squarely at the fixation point, or very close to it, as Miss Carter's first experiments showed. Enough locations must be included throughout the matrices to make it appear that the critical element may lie anywhere in the matrix. Nevertheless, in only a few special experiments, with a basic matrix of a single size, has it been feasible to place the initial element in every possible position. This is why we speak of "sampling" the positions within the matrices.

E. Variables in these Experiments

It may help to set our experiments in perspective if we next list the variables (or groups of variables) that can be found in them. The list is long, but does not pretend to be complete. The variables are grouped under the headings of stimulation, instruction, and response. Comments are added to some items for their definition or explication.

Variables of stimulation

1. Number of elements in the array.
2. Area covered by the array, as projected.
3. Surface density of the array. This is the number of elements (or the mean number) per unit area. It turns out to be an important variable.
4. Regularity of arrangement.

   Most of our experiments have used rectangular matrices, a regular arrangement of the elements.

5. External shape of the array.

   We have used squares, rectangles, linear arrays and some irregular shapes.

6. Variables that distinguish the critical elements from the background elements.

   We have used form (triangle vs. circles), area, hue, for example.

7. Degree of difference between the critical elements and the background elements.

   This variable should control the difficulty of the discrimination, other variables being held constant.

8. Spatial dimensions of the critical element and the background elements.

9. Viewing distance.

   Together with 8, this variable determines angular size and controls acuity, other variables being held constant.

10. Luminance of the elements, and of the ground, as projected.

11. Duration of exposure.

    Obviously a principal independent variable.

12. Number of critical elements.

    One, in our experiments.

    Zero for the "blank" stimulus arrays.

13. Variables characterizing the ready stimulus.

14. Variables characterizing the fixation or pre-exposure field.

15. Variables characterizing the post-exposure or erasing field.

16. Statistical uncertainties of the location of the critical element in the array. One should consider both the sampling of locations and the randomizing of the order of presentation.

17. Statistical uncertainty of the area of the array, determined by the randomizing of various areas. Zero for the block presentation used in some of our experiments.

Variables of Instruction

Systematically considered, these are also stimulus variables, but they form a different class of stimuli: verbal, contained in prepared instructions read to S, and reiterated. Some experimental psychologists prefer to minimize instructions. Our policy has usually been just the opposite: to write out detailed instructions, with the aim of placing under some measure of control as many variables as possible.

Some of these variables appear also in the other lists. They appear here because the S may be set to respond selectively to them as a result of instruction.

1. Variables of readiness, pre-exposure and fixation.
2. Aspect to be discriminated: form, area, hue, e.g.
3. Number of critical elements in the array.

   In our experiments, one or zero.

4. Uncertainties of area or shape of array, location of critical element, etc.
5. Variables of the "method" or the pattern of search.

   Left unspecified in most of our experiments; or "any method you find best".

6. Speed of search.

   In our experiments, S was set to find the critical element as soon as possible.

7. Variables of response-topography; the bodily member to be moved and the direction of its movement.

   Here, a forward pointing movement of the right forefinger.

8. Speed of response.

   S was set to snap the finger forward.

9. Confidence criterion; related to it, the operating characteristic.

   Not specifically controlled by instruction in our experiments; influenced by other variables.

Variables of Response

1. Response topography

   As above, except that these variables would describe the response objectively.

2. Postural preparation for the response.

3. Phase of the response at which the timing is triggered.

   If the response is actually the one whose latency is to be determined, the timing should be triggered early in that response.

4. Confidence-criterion (or the related operating characteristic) of the response.

   How confident must the S be before he responds? - The response may be verbal, manual, etc.

5. Response latency, as measured.

   This is the principal dependent variable in most of our experiments.

6. Mechanical force of the response.

7. Velocity of the response-movement.

8. Confidence attending the response.

   Not recorded in these experiments, although it frequently is an interesting dependent variable.

9. Accuracy of the locating response.

   Only estimated in our experiments.

10. Accuracy-criterion of the locating response.

    How close must the locating response be to the position of the critical element to be considered as correlated with it?

11. Proportion of positive judgmental responses, verbal or other.

    This is the principal dependent variable in some of our later experiments.

These lists of variables come from an inspection of our experiments, following the experimentation. They also come from an older list of variables of human judgment, and a list of variables in the reaction-time experiment. We are making here a kind of operational analysis, which might well be extended to other fields of psychological research. Many of the same variables will recur time after time, even in experiments that seem at first glance to be quite unrelated.

The list of variables should set into perspective one type of experiment, already described, in which the S searches for the single critical element while the stimulus array remains exposed. The locating response terminates the exposure, and the latency of this response is the principal dependent variable. For convenience, let this be called the method of lasting exposure.

There are many other possible methods; one of them may be called for our purposes the method of brief exposure. In this method, the S sees a brief exposure of constant duration; if she is able to locate the single critical element, she responds positively (verbally or otherwise). The principal dependent variable is the proportion of responses that are positive. She makes a subsequent locating response, which E checks.

There are other methodological features that do not enter the list of variables above, and that are treated elsewhere in this report. The stimulus arrays may be typed out on sheets and presented with an opaque projector. They may be prepared (and changed) by using a diazo process, as described in some detail in Appendix A to this report. The product goes into an opaque projector; in some forms, it could perhaps be projected as a transparency. Or the entire array can be fabricated as a pattern in a metal sheet, and illuminated from behind with a projector beam: the system used in one experiment to be described later.

III. Results: the Critical Number

A. A Gross Linear Relation

Coming out of the methodological woods, we face the pleasant prospect of some results. Miss Carter's experiment covered a wide range of the independent variable number-of-elements, from 2 to 3600. To show the results most clearly, it will be necessary to graph them in two ranges. The two ranges overlap, and it will eventually be clear that the results of the two analyses are consistent.

The first range to be considered extends from 100 to 3600. The principal dependent variable is the median latency t_{mdn}; the median rather than the mean, because the distributions of latencies are as usual skewed. Figs. 7 and 8 present the data of two S's plotted on arithmetic coordinates, with median latency in secs. as a function of number-of-elements. The number is the total number of background elements and the critical element.

The relation is nearly linear over this wide range; a wider range than that explored in former experiments (Anderson and Green [4]). Those experiments also found an approximate linear relation. The result is a very reasonable one: one might expect that the greater the number of elements to be searched in almost any manner, the longer the time it would take (on the average) to find a particular element. Ezra Krendl of the Franklin Institute and William McGill of Columbia have been interested in specific mathematical models for the latencies of search.[6,7] It is our feeling that the linear relation is a statistical product of several quite different search "methods" to be untangled first by experimental means. Some suggestions about the tangle will be offered later in this report.

The slope of the straight line varies from S to S. In the results of Miss Carter's 6 S's, the lowest slope was 0.0012 and the highest 0.0027. One S gave an abruptly shorter median time at the largest matrix (3600 elements): an indication that she might have recognized a few locations of the critical element very near the edge of the screen. There was no other apparent difficulty of this kind.

The variability of the latencies was also related to the number-of-elements

Fig. 7

Showing for one S(CS) the median latency in secs. as a function of the number of elements in the matrix, for numbers of 100 and above. 100 observations per point. Arithmetic coordinates. (After Carter).

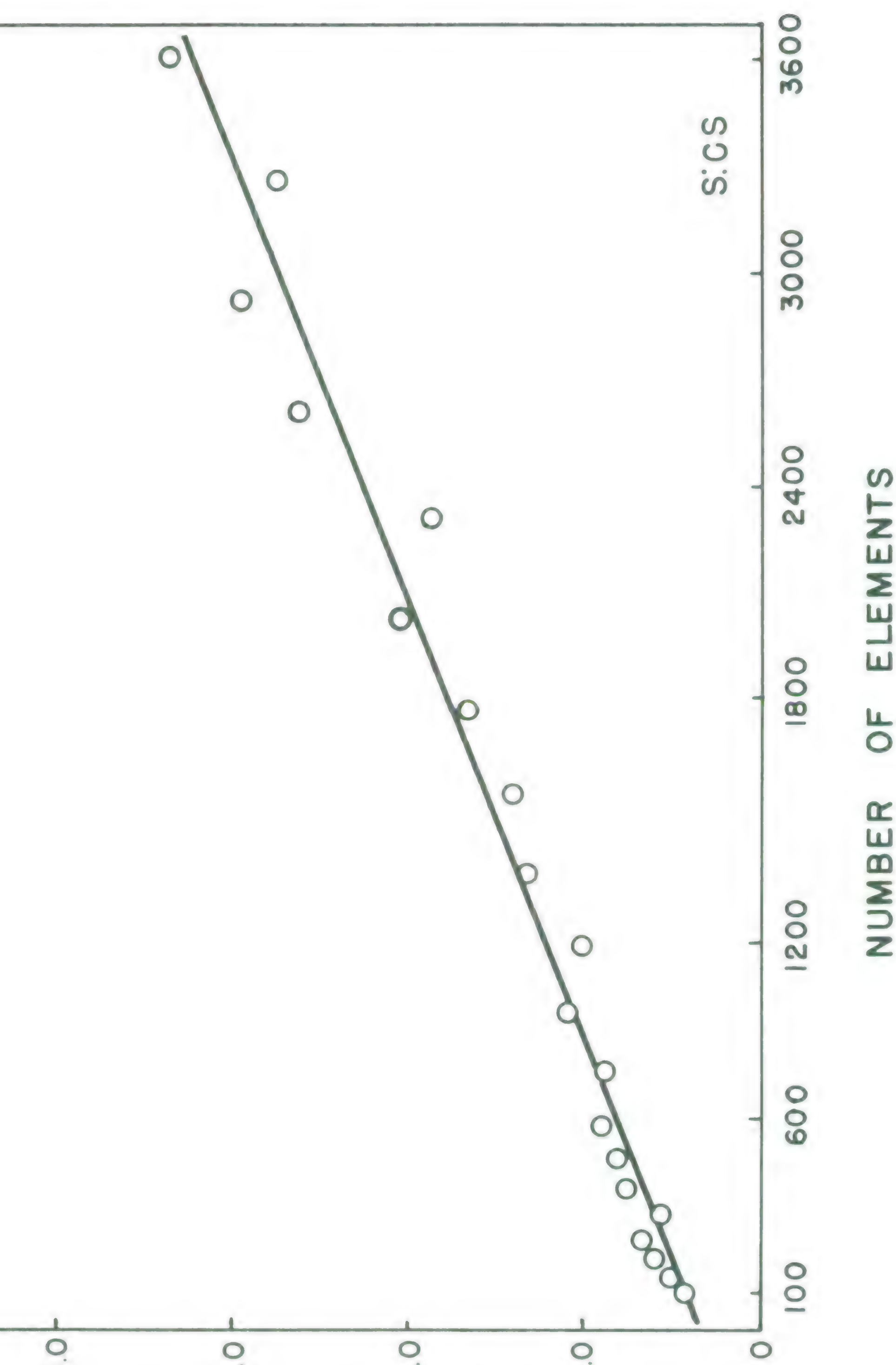
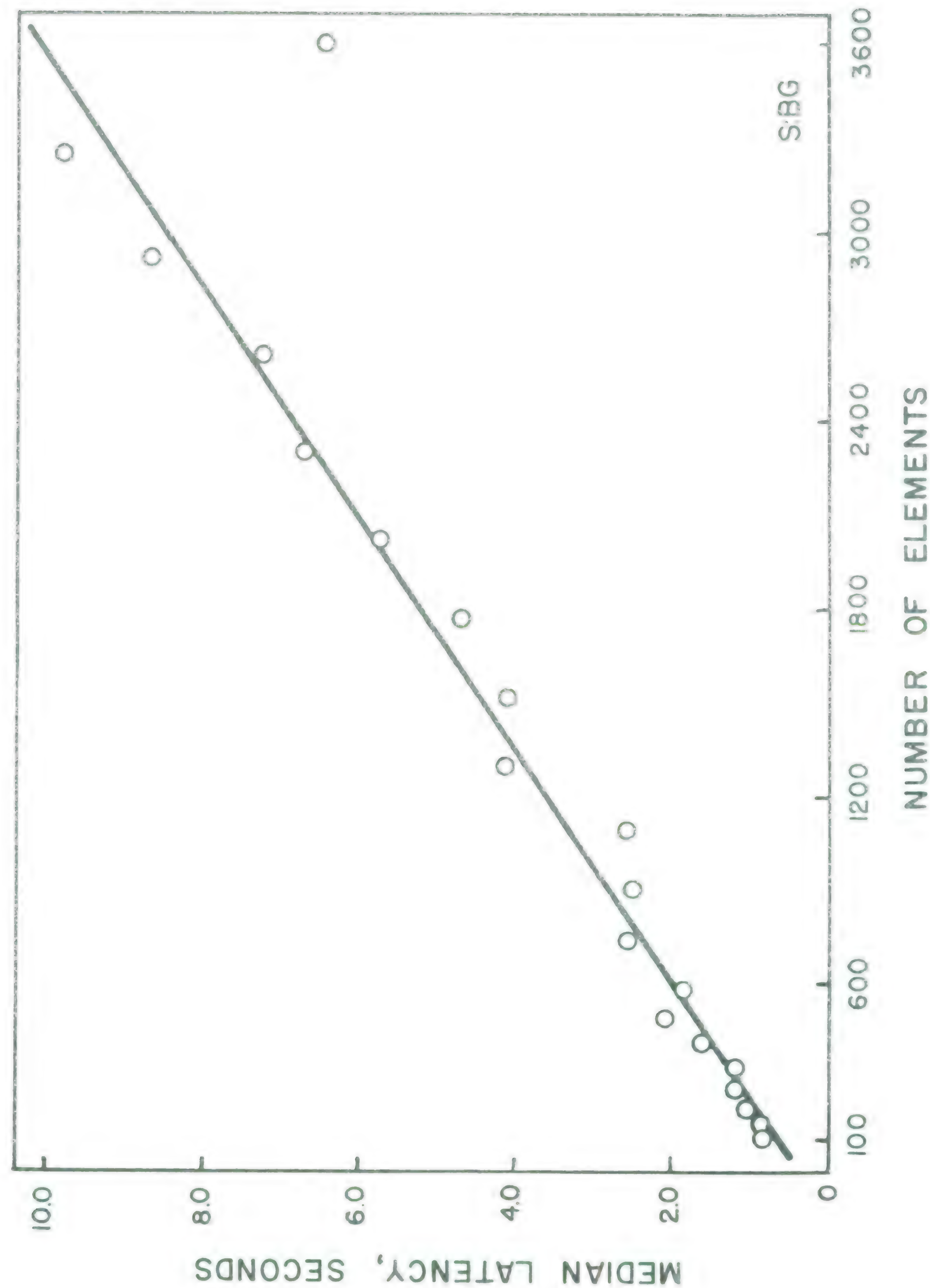

S:CS
MEDIAN LATENCY, SECONDS
0
2.0
4.0
6.0
8.0
10.0
NUMBER OF ELEMENTS
100
600
1200
1800
2400
3000
3600

Fig. 8

Showing for one S(BG) the median latency in secs. as a function of the number of elements in the matrix, for numbers of 100 and above. 100 observations per point. Arithmetic coordinates. (After Carter).


S:BG
MEDIAN LATENCY, SECONDS
NUMBER OF ELEMENTS
0
2.0
4.0
6.0
8.0
10.0
100
600
1200
1800
2400
3000
3600

over the range 100-3600 elements, although the apparent form of the relation varied somewhat from S to S. For 3 of Miss Carter's S's the relation was linear; for the other 3, slightly concave upward.

B. Evidence for the Critical Number

Our laboratory group has been more interested in what happens in fast search, comparable to the field or span of attention in classical experimental psychology. The first two graphs show on logarithmic axes the median latency as a function of number-of-elements from 2 to 3600 (see Figs. 9 and 10). The latencies undergo a small, very gradual increase, an abrupt transition, and a faster increase. The transition may be seen in these graphs as a small first-order discontinuity or as a second-order discontinuity (a discontinuity of slope). In other experiments it appears as a short sigmoid section between branches of the function. Nevertheless, in almost all of our results, covering some years of research, it has been possible to locate a transition of some kind that marks off a lower branch of the function from an upper one.

If we think for the time being only in terms of the independent variable number-of-elements, the transition defines what we shall call the critical number (CN). The CN is usually stated here in terms of its apparent limits: the two stimulus values that bound the transition. So the CN in Fig. 9 would be 81-100; in Fig. 10, 144-196. If a single number is required, the median of the two limits is the best estimate available. Occasionally the CN seems to lie so close to a particular stimulus value that this single value is stated, instead of two limits.

The other 4 S's in Miss Carter's experiment yielded data very similar to those shown in Fig. 9 and 10. The CN's for these S's lay between the extremes shown in the two figures. For all 6 S's, then, the order of magnitude of the CN was the same. Nevertheless there were individual differences, a finding that helps to ensure that the transition is not due to an artifact of stimulus or method.

Fig. 9

Showing for one S(SH) the median latency in secs. as a function of the number of elements in the matrix, for all numbers of elements. Logarithmic coordinates. 100 observations per point. (After Carter).

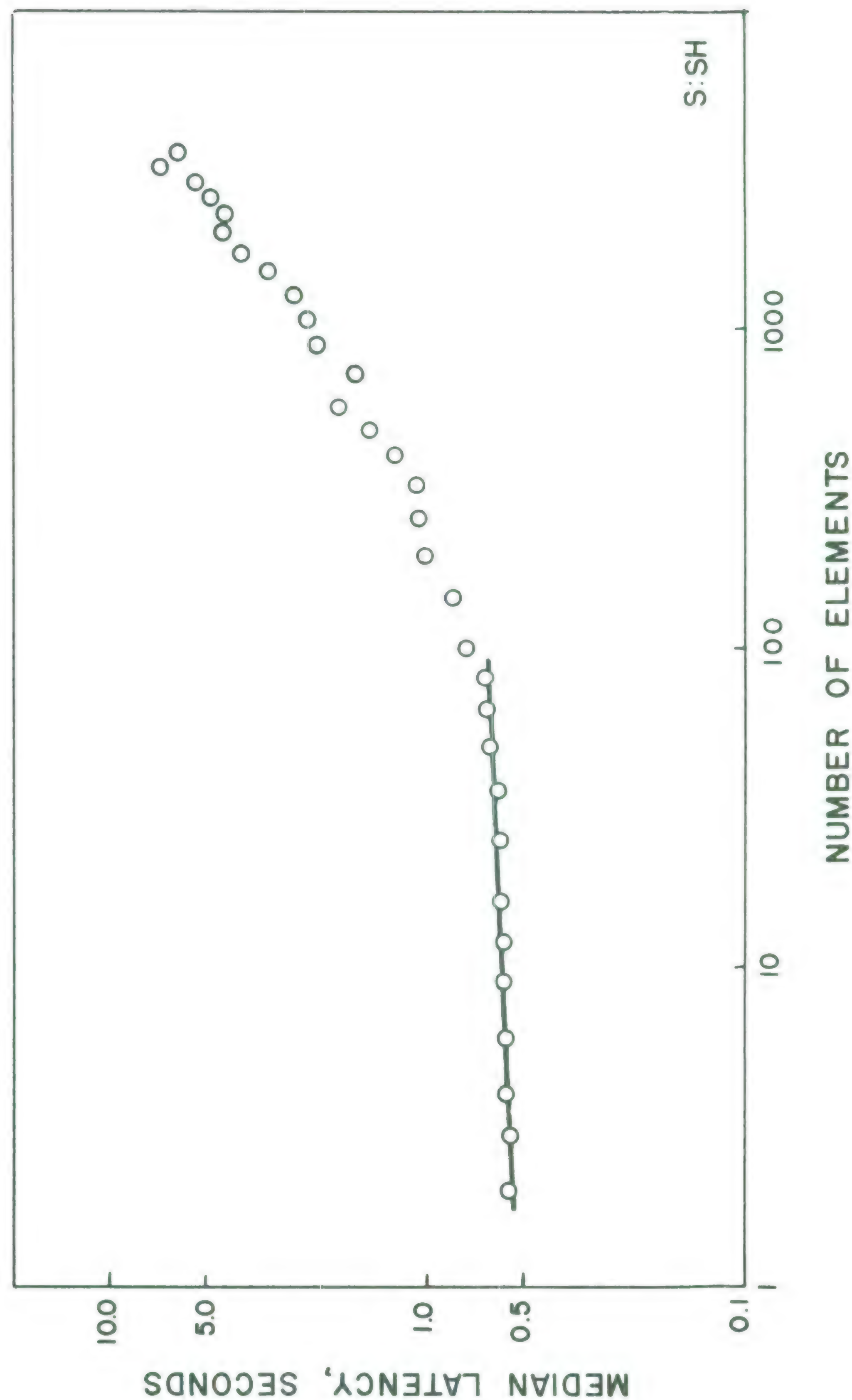
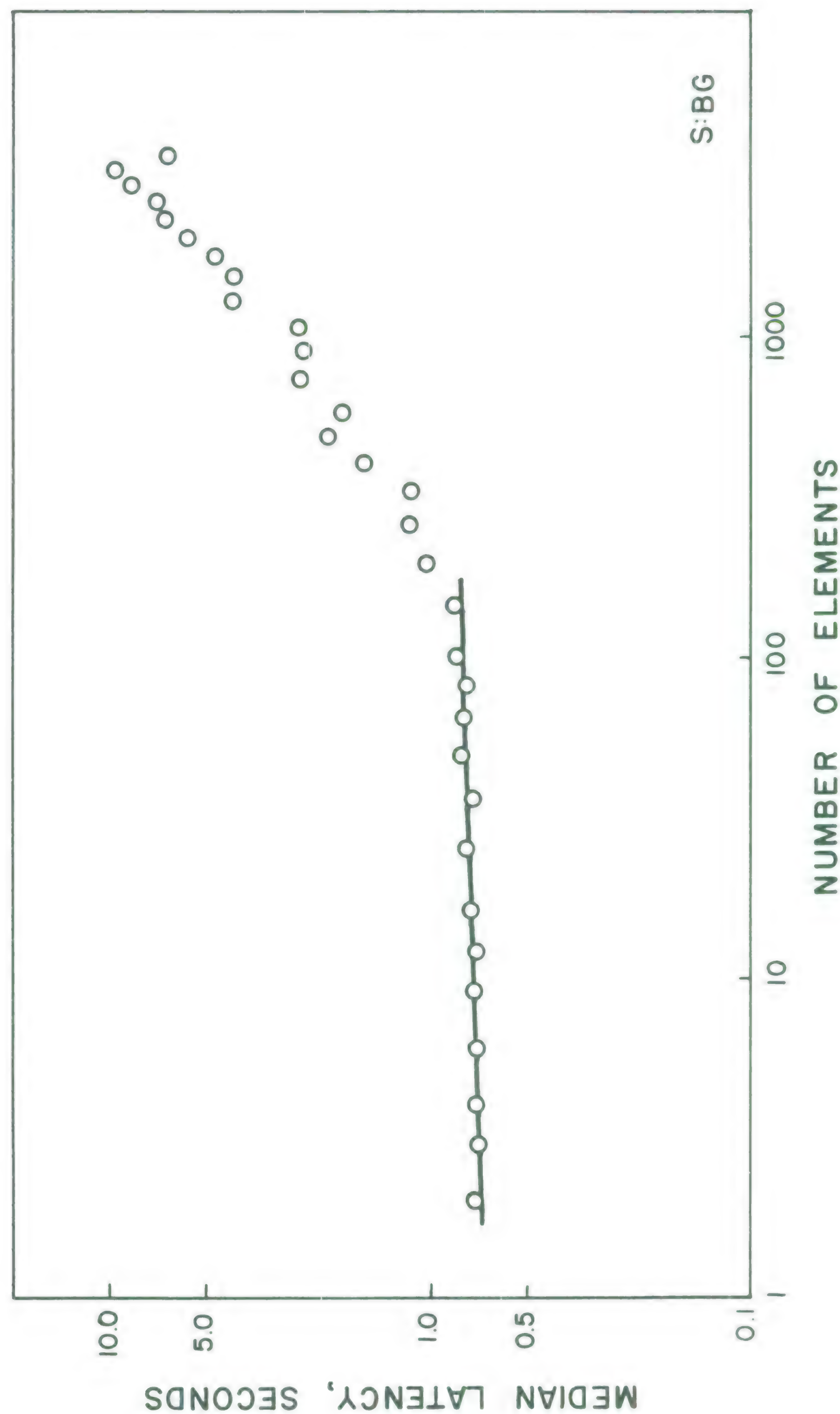

S:SH
NUMBER OF ELEMENTS
1
10
100
1000
MEDIAN LATENCY, SECONDS
0.1
0.5
1.0
5.0
10.0

Fig. 10

Showing for one S (BG) the median latency in secs. as a function of the number of elements in the matrix, for all numbers of elements. Logarithmic coordinates. 100 observations per point. (After Carter).


S:BG
MEDIAN LATENCY, SECONDS
10.0
5.0
1.0
0.5
0.1
NUMBER OF ELEMENTS
1
10
100
1000

More recently Miss Coonley and Mrs. Eddy have duplicated most of the stimulus conditions of Miss Carter's experiment, but have used the improved method previously described. The S searches for a triangle in matrices otherwise composed of circles, and square in external shape. The range of number-of-elements was shorter than Miss Carter's: 25-529. Figs. 11 and 12 show the data for two S's; the other 4 yielded very similar data.

The figures have as a reference line the median latency for a target lying at the fixation point, or very close to it. This latency is nearly constant over the whole range of matrices, as might be expected. The median latency for all target locations, the principal datum, begins at the same level and increases only slightly above the reference line; then it diverges upward, thus locating the CN. There are plainly two regions of the curve: one lying close to the reference line, the other diverging widely from it. The original finding of the CN is confirmed.

C. Variability and Practice

The topics of variability and practice need to be examined briefly. Miss Carter plotted for each of her 6 S's the semi-interquartile-range Q of the latencies at each number-of-elements. The graph for two of the S's suggest a discontinuity in the region of the CN as previously defined; the graph for a third is doubtful; the graphs for the other three S's are sensibly continuous. If the CN is to be located with the aid of variability measures, the methodology will need to be better.

With respect to practice: it is important to distinguish between the effects of practice upon latency from those upon the location of the CN.

Miss Carter compared the median latencies for the first half of her experiment with those for the second. All 6 S's showed a decrease in latency significant at the .01 level (Wilcoxon matched-pairs signed-ranks test). The practice-effect is most reasonably interpreted as the adoption by each S of more efficient "methods" of search as the experiment progressed.

Fig. 11

Showing for one S(Gr) the median latency in secs. as a function of number of elements. The axes are logarithmic. Median for the central location of the critical element and all locations of it are plotted separately. There are 20 observations per point for the central location and 120 for all locations.

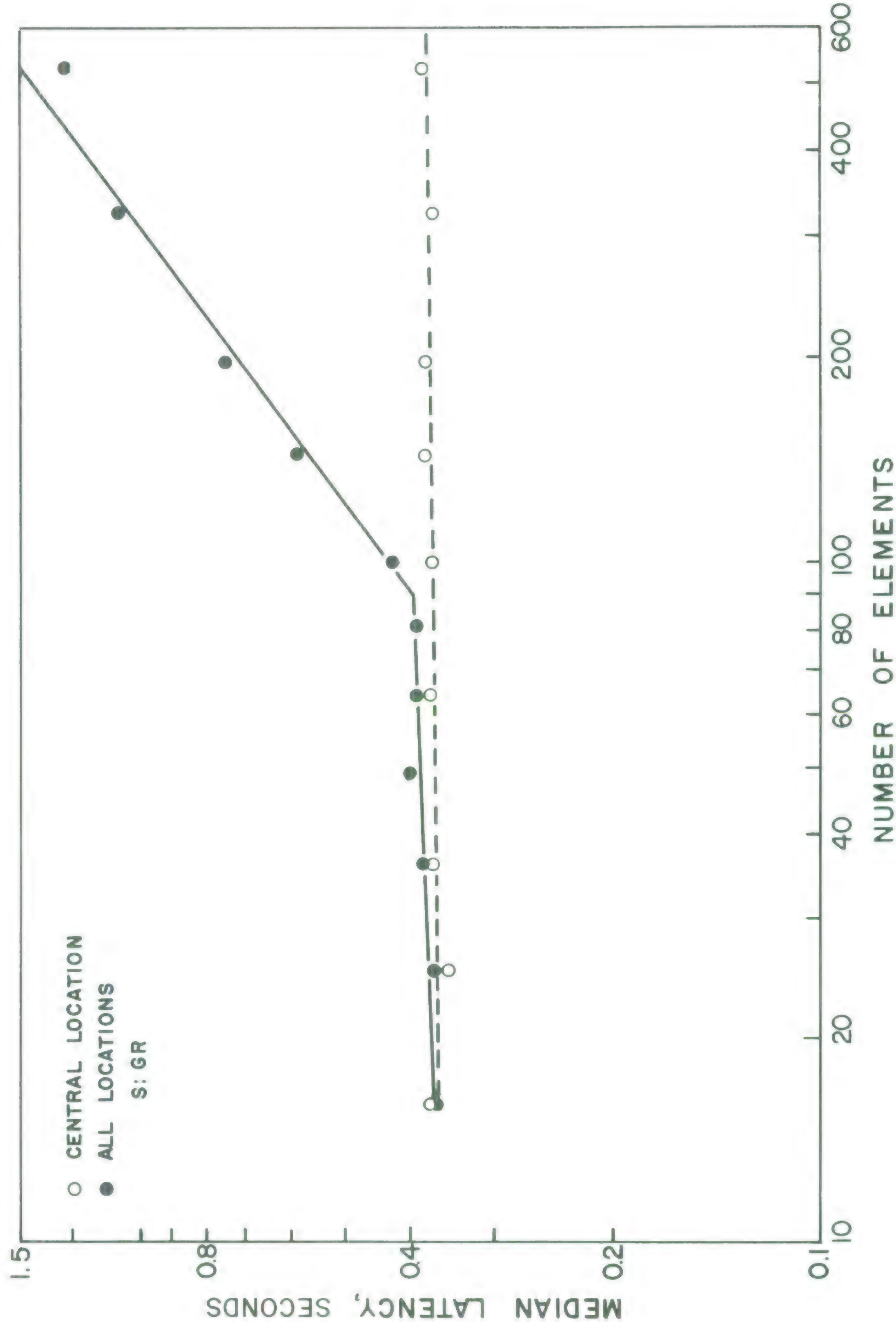
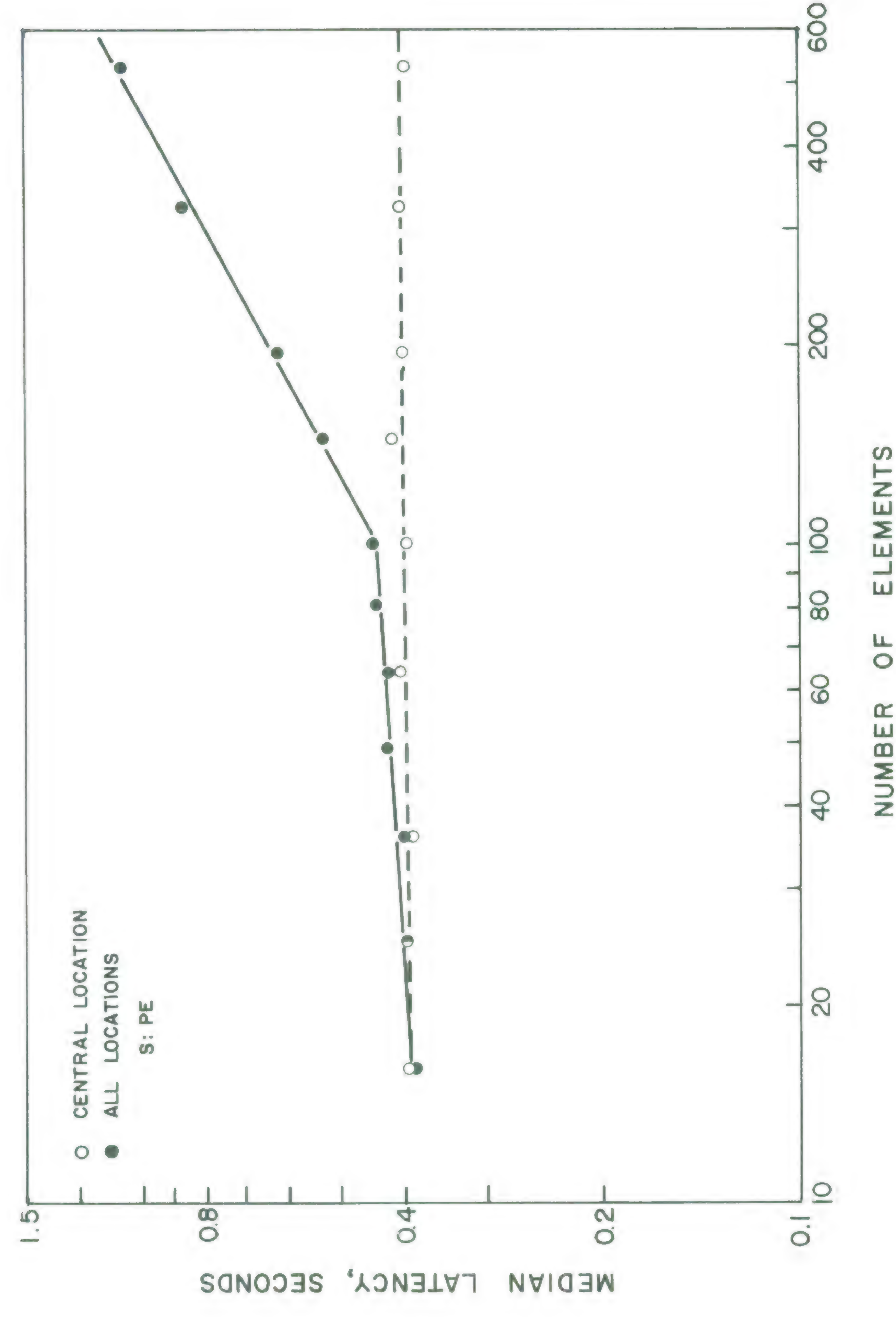

MEDIAN LATENCY, SECONDS
NUMBER OF ELEMENTS
CENTRAL LOCATION
ALL LOCATIONS
S: GR
1.5
0.8
0.4
0.2
0.1
10
20
40
60
80
100
200
400
600

Fig. 12

Showing for one S(Pe) the median latency in secs. as a function of number of elements. The axes are logarithmic. Medians for the central location of the critical element and for all locations of it are plotted separately. There are 20 observations per point for the central location and 120 for all locations.


CENTRAL LOCATION
ALL LOCATIONS
S: PE
MEDIAN LATENCY, SECONDS
1.5
0.8
0.4
0.2
0.1
NUMBER OF ELEMENTS
10
20
40
60
80
100
200
400
600

Miss Coonley and Mrs. Eddy carried out a more elaborate graphical analysis, plotting different curves of mean latency for each successive quarter of the data. Because of the reduced N, the individual datum-points are relatively unreliable. Nevertheless, some statements can be made as follows:

1. All 6 S's showed a considerable reduction in latency above the CN.

2. Five of the 6 S's showed a small or very small reduction in latency below the CN.

3. As well as could be determined, considering the limited reliability of the data:

a. Four of the S's showed no change in the location of the CN with practice.

b. The other two S's showed a shift upward of the CN by one datum-point from the first quarter of the data to the succeeding quarters.

D. An Interpretation of the Critical Number

Perhaps the most striking feature of the results is that they provide in the CN a measure that is far higher than the range of attention as classically determined. There is apparently a process of fast search that can deal in some restricted fashion with as many as 170 elements in a matrix. The results to be shown in later sections will extend this figure into the thousands. By restricting the S's task, by avoiding the limits of short-term memory, and by employing the variable of number-of-elements, we have come much closer to measuring the detail that is present in the visual field.

There is no claim that the CN is an invariable point-magnitude, or a point-magnitude at all. Yet one can often state the CN as lying between two adjacent stimulus values, as in Figs. 9 and 10 above. The relative variability of the CN can apparently be far less than the relative variability of the range of attention. In an experiment on the range of attention, S will sometimes report correctly 3 capital consonants, sometimes 4, sometimes 5, and so on. The range is then statistically defined as a limen: the number of

consonants reported correctly 50% of the time. Some of this variability that forces a statistical treatment must be due to the processes of short-term memory.

In transcending the limits of the range-of attention experiment, we have naturally not transcended all of the research connected with it. A nice example of relevant research is Chapman's thesis concerning the reciprocity of range and clearness.[8] The thesis might be stated in terms of information: the less information-per-item we demand of the S, the more items he can report on correctly. We have asked very little of the S's in our experiments: only the general location of an element that resembled a triangle much more than it did a circle. We did not ask for its precise location, nor did we require the inspection of each of the other elements to insure that no one of them resembled a triangle in any way. Consequently the finding of a large CN, analogous to a range though differently defined, is quite consonant with Chapman's thesis.

Our interpretation has a background and a defense in systematic psychology and in the computer sciences, but all such material lies outside the scope of this report. The terminology is obvious enough: display, storage, retrieval, etc. Some of the suggested relations between computers and humans are much less obvious, and much more problematical. Let us state them nevertheless.

The phenomenal field, including the visual field, is a display of information. Most of the information, but not all, comes from the sensory input channels. The display differs from those that engineers design in one important respect: there is nobody watching it. The phenomenal ego is itself a built-in, structural feature of the display. What the display accomplishes is the very-short-time storage of a vast amount of information, only a small proportion of which is retrieved from the display for the longer-time storage of memory. The set that S assumes, the task that we assign him (or that he

assigns himself), the method by which he accomplishes the task: all these correspond to pre-prepared programs stored in the S's internal library. From the standpoint of this particular systematic psychology, the big question is no longer, "Is man a computer?" It is rather, "What kind of computer is a man?"

We hypothesize a fast search process, where "fast" means one tenth of a second or a few tenths of a second. The search process is analogous to the retrieval of information from a storage matrix in computer practice. Indeed, we may some day conclude that physiological matrices of various types are responsible for the display and storage of information in the human. These underlying, hypothetical matrix mechanisms must of course be distinguished from the stimulus matrices which one may present, and from the phenomenal display of those matrices. The mechanisms of phenomenal display, whatever they may be, do a superlatively good job of displaying information that is not in matrix form at all.

We further hypothesize that fast search and the CN are related to saccadic search behavior. In its simplest form, this relation might be described as follows:

1. The eyes are fixated at or near the fixation-mark when the lasting exposure begins. The fast search also begins, and continues without major eye-movements in a region around the fixation-point until the incoming visual information reaches some limit. It is a basic, long-range research task to determine and specify this limit. As explained below, the CN reflects this limit under the conditions of our experiment.

2. If the information sought-for is retrieved (in ordinary language, if the S finds the critical element) a saccadic eye-movement occurs in the direction of the critical element. The manual response is also triggered off.

3. If the limit is reached without retrieval (i.e., if S does not find the critical element), a saccadic movement occurs to a new locus, and a new fast search process begins. When the limit is reached, the saccadic movement and the following search process produce the transition to a slightly higher median latency. The saccadic movement alone will not account for the transition, since it occupies only about 25 ms. The exhaustive search of stimulus arrays containing more than the limiting amount of information is performed with a series of saccadic movements and intervening fast searches.

4. Since fixating and saccadic behavior is presumably shaped operant behavior, we would expect different S's to have different, and possibly characteristic, patterns of saccadic search. If the critical element does not appear on the initial fixation and fast search, one S might look next to the right; another S might look next upward, and so on.

5. The search of relatively large stimulus-arrays may follow regular scanning patterns, similar to the sawtooth patterns long ago recorded in reading.

In considering the above, one must remember that it is purely hypothetical. We have obtained as yet no evidence concerning eye-movements, and are just now beginning to design a special optical system for photographing them in our search situation. The conjunction of photographic and psychophysical evidence should be illuminating.

To return briefly to the results: the graphs show a slight increase in latency up to the CN. This increase might be thought to measure the time taken for the fast search process to run its course and reach its limit. This would be an interesting measurement indeed. A more likely interpretation is that the rise in median latency represents a statistical admixture of cases in which a saccadic movement occurs <u>before</u> the limit of search is reached

with the initial fixation. Operant shaping might produce such hasty search behavior. Only a long series of eye-movement photographs in our situation could point out the proper interpretation.

Our measure, the CN, is stated in terms of number-of-elements, even though number and area are confounded in most of the experimental designs. To be clear, one must speak in terms of number _or_ area, rather than in terms of "matrix size", even if the number and area are confounded in the experimental design. (The theses from our laboratory have not always been clear in this respect). The concentration upon number reflects the background of the range-of-attention experiment. For a time we entertained the idea that, for any given discrimination, the CN would be independent of area and of density within wide limits. The limiting variable would be the sheer number of elements or items to be processed in the search.

The idea turned out to be wrong. The research that showed it to be wrong was not easily done, and actually came after the research covered by this report. To take another problem, it seemed likely from the first that the CN would vary with the particular discrimination required of the S. This expectation rested upon the reciprocity of range and clearness, referred to above. The experiments to be described in a later section bore out this expectation.

E. _The Initial Sub-Matrix_

What happens when a matrix containing more than the critical number of elements is exposed? The hypotheses stated above offer an answer. It depends on the location of the critical element. If the critical element lies very close to the fixation point, the response latency should be substantially independent of number-of-elements and matrix area. (We have already seen that it is). If the critical element lies further away from the fixation point, we must distinguish between two cases, and must rely for the

distinction upon the value of the CN determined for an individual S in an actual experiment. There will be a portion of the larger matrix, perhaps the portion lying symmetrically about the fixation point, that contains a number of elements equal to the critical number. The initial process of fast search covers this part of the large matrix very soon after the exposure begins. This part of the larger matrix can conveniently be called the _initial sub-matrix_.

If the critical element lies within the initial sub-matrix, the latency should be only slightly longer than the latency for a critical element lying at the fixation point. Theoretically, the additional time is that required for the process of fast search. The latency should also be substantially independent of the number of elements in the larger matrix and of the area covered by the larger matrix. In ordinary (and very inadequate) language, the S picks out a part of the large matrix right around where he is already looking, and finds the critical element within it. It does not matter what the rest of the matrix is like.

On the other hand, if the critical element lies _outside_ the critical sub-matrix, more than one fixation and fast search process are required to find it. The median latency should be longer than the latency for a centrally-located critical element, and longer than that for critical elements lying outside the center of fixation but inside the initial sub-matrix. Further, it should increase with the number of elements in the whole matrix and the area covered by the matrix, since repeated fixations and fast searches will be required to find it.

The analysis of the data requires that the latencies for different locations of the initial element be separated. This can be done. It also requires that particular locations be identified as lying either inside or outside the initial sub-matrix. This in turn requires assumptions about the

shape of the region of fast search, such as the assumption made above, in speaking of a portion of the larger matrix lying "symmetrically" about the fixation point. We are only now beginning to obtain information about the shape of the region of fast search. Nevertheless, the assumption must be relatively uncritical, because it has not been difficult to produce analyses of data that are quite consistent with the idea of the initial sub-matrix.

Miss Stanley varied systematically the radial distance of the critical element from the center of the matrix (the initial fixation point).[9] The distance was determined not absolutely, but relative to the radius of the individual matrix. Her method included the feature of block presentation, discussed critically in a preceding section. The median latencies and the variability Q increase with the radial distance of the critical element from center.

Another analysis comes from a more recent experiment by Miss Coonley and Mrs. Eddy. They used the improved method previously described, and the familiar discrimination of a triangle in an array otherwise composed of circles. The arrays were internally regular: the elements were arranged in rows and columns like Miss Carter's. (The external shape of the arrays was irregular, i.e. blob-shaped, although for the purposes of the present discussion it could just as well have been square, or some other regular shape). The analysis yielded three sets of median latencies, the first set being the latencies for a central location of the critical element. To obtain the second set, a square was drawn symmetrically about the central location, so as to include a number of elements equal to the critical number. The square approximates the initial sub-matrix. All locations lying within the square yield the second set of latencies. The third set consists of latencies for locations of the critical element lying anywhere in the blob-shaped array outside the square. Figure 13 and 14 show plotted points for the three

Fig. 13

Showing for one S(Gr) the median latency in secs. as a function of the number of elements in the array. The external shape of the array was irregular; the internal pattern,regular. Medians for the central location of the critical element, for the locations of it inside a square corresponding to the initial sub-matrix, and for locations outside this square, are plotted separately. Arithmetic coordinates. 20-120 observations per point.

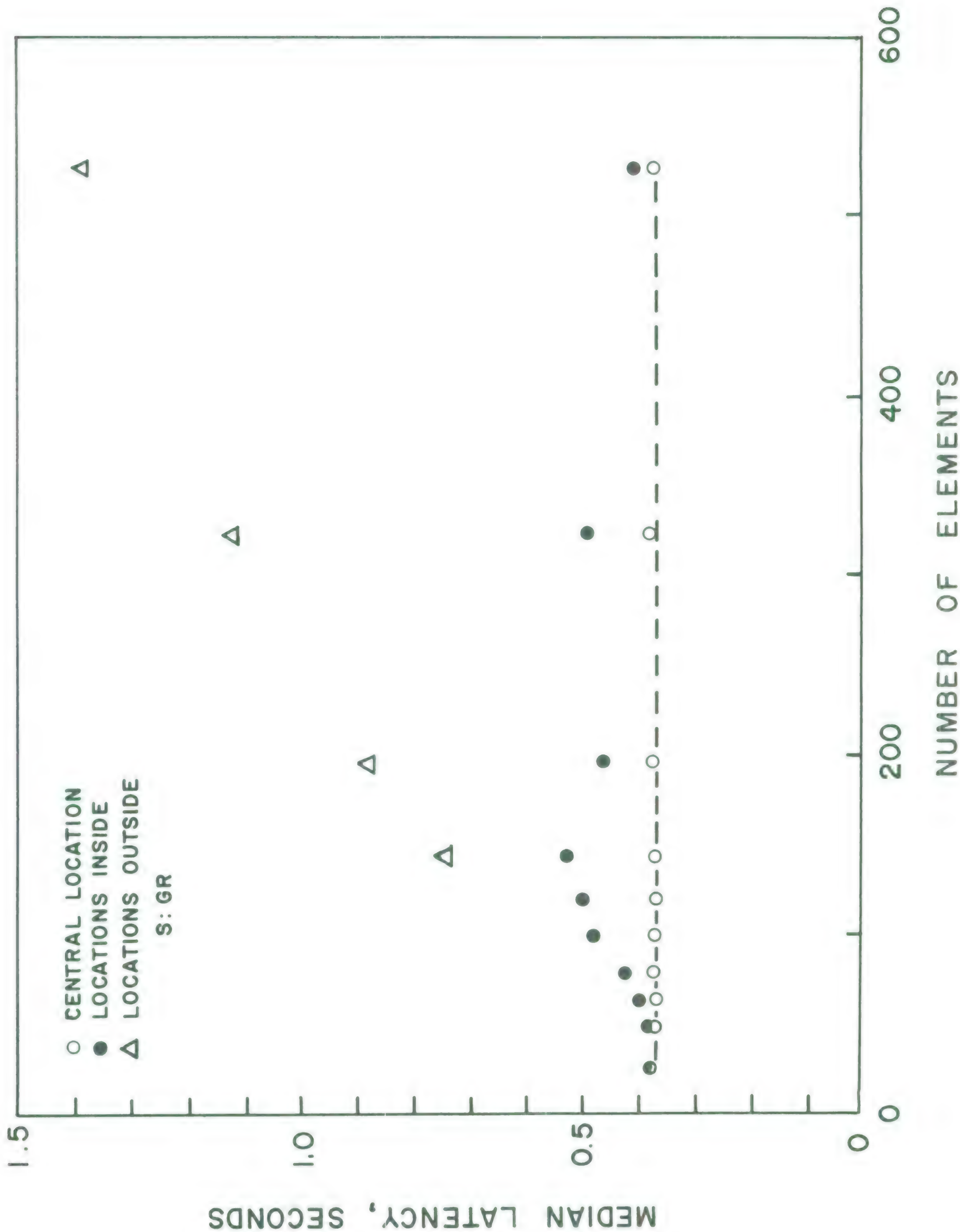
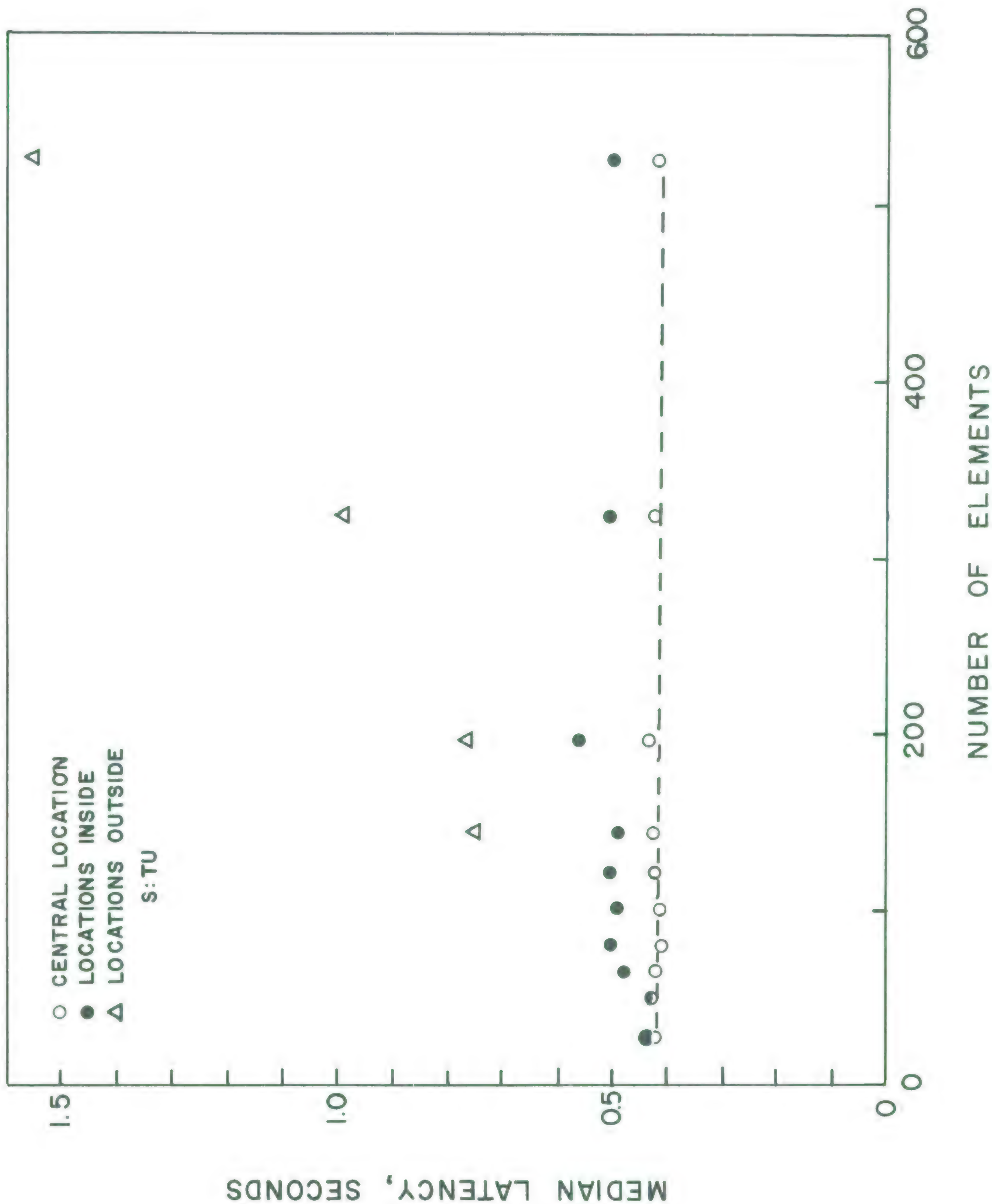

CENTRAL LOCATION
LOCATIONS INSIDE
LOCATIONS OUTSIDE
S: GR
MEDIAN LATENCY, SECONDS
1.5
1.0
0.5
0
NUMBER OF ELEMENTS
0
200
400
600

Fig. 14

Showing for one S(Tu) the median latency in secs. as a function of the number of elements in the array. The external shape of the array was irregular; the internal pattern, regular. Medians for the central location of the critical element, for locations of it inside a square corresponding to the initial sub-matrix, and for locations outside this square, are plotted separately. Arithmetic coordinates. 20-120 observations per point.



○ CENTRAL LOCATION
● LOCATIONS INSIDE
△ LOCATIONS OUTSIDE
S: TU
MEDIAN LATENCY, SECONDS
1.5
1.0
0.5
0
NUMBER OF ELEMENTS
0
200
400
600

sets of latencies for two of the S's. The plots for the other 4 S's are similar.

The points describing the middle curve represent the latencies for locations of the critical element lying within the square. These points are not much higher than those for the central location, and they increase very little with the number of elements in the matrix. The upper set of points, for locations of the critical element outside the square, increase markedly with the number of elements. One must note carefully that Figs. 13 and 14 do not provide additional evidence of a transition because the datum-points depend on the assumption of a transition.

These results are completely consistent with the idea of an initial sub-matrix. The S finds the critical element rapidly within this sub-matrix, regardless of the area or shape of the matrix as a whole. Yet it can be argued that the results are also consistent with a much simpler principle, and that we have not demonstrated the thesis of the initial sub-matrix at all. The simpler principle is that the latency increases with the radial distance of the critical element from center. The middle set of points in the graphs merely represents locations of the critical element near the center.

In order to answer this objection, we would first need to establish the shape of the region of fast search (if it has a definite shape). Then we would need to show that locations just inside the region of fast search yield latencies like the middle set of points in the figures, whereas locations just outside yield latencies like the top set of points. Unfortunately, this is not yet possible to do.

F. An Experiment with Brief Exposures

Dr. Corbin and Miss Stanley displayed that mixture of skepticism and curiosity which scientists aim at, but do not always achieve. They suspected

that our findings concerning latency and the CN were related to the method of lasting exposure and that they might not appear with fixed, relatively brief exposures. So they devised an experiment in which the stimulus matrices were exposed for a limited time. The limit was a time just longer than the basal latency of the particular S: the time needed to respond to the smallest matrices. If the S responded before that limit, the field went off with her response. The S searched for a large solid black circle (0.71 in diameter as projected) in a matrix otherwise composed of small solid black circles (0.57 in diameter). There were three S's in this experiment.

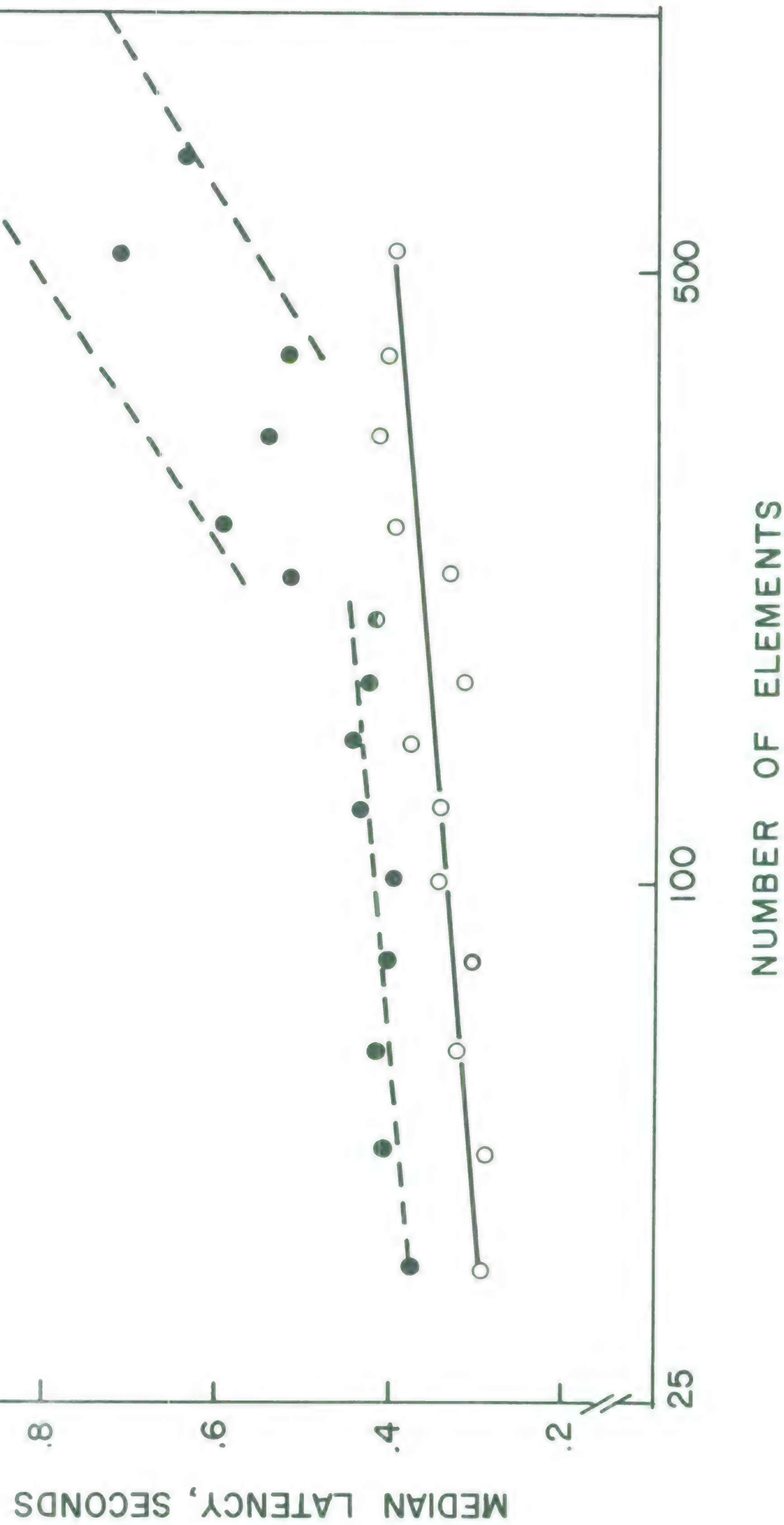
Miss Stanley's experiment had methodological difficulties, mentioned below, but it yielded results so striking that they must be considered here. Fig. 15 shows for one S the median latency plotted against the number of elements (semi-logarithmic axes). One set of data comes from the experiment with brief exposures; the other set from the experiment with lasting exposures (same S). The first finding is that the median latencies are shorter for the experiment with brief exposures. As Miss Stanley observes in her thesis, the search is (or can be) more "efficient" under these conditions. One other S shows a similar advantage of the brief exposures. The third S showed about the same latencies for the two experimental conditions.

With brief exposures, the critical element was frequently not seen at all. Miss Stanley adopted the convention of an infinite latency for these cases. In consequence, no median could be computed for the two top points of the lower curve in Fig. 15. The convention does not alter the inference of reduced latency for brief exposures, because its effect is to increase the computed median latency rather than to reduce it.

The second finding is that there is no discoverable transition in the curve for brief exposures, hence no CN. At first glance, this finding would suggest the CN is indeed some artifact of the method of lasting exposures,

Fig. 15

Showing for one S(KY) the median latency in secs. as a function of the number of elements in the matrix. The S searched for a large black circle in matrices otherwise composed of small black circles. The medians for lasting exposures and brief exposures are plotted separately. Semi-logarithmic coordinates. 24 observations per point. (After Stanley).


MDN. FOR LAST 4 TRIALS, LASTING EXPOSURES
MDN. FOR BRIEF EXPOSURES
1.0
.8
.6
.4
.2
MEDIAN LATENCY, SECONDS
25
100
500
NUMBER OF ELEMENTS

and of little general interest. This is not our view. The clue to a different interpretation comes from a statement of Paul Fitts, to the effect that a saccadic eye-movement is unlikely to occur within the brief times used in this experiment.[10] Faced with brief exposures, the S apparently holds his initial fixation, and extracts as much information as possible from the brief exposure. Precisely because there is no saccade and following fast search, there is no transition in the lower curve of Fig. 15, hence no evidence of a CN. The CN is not an incidental artifact of the method of lasting exposure, but a very significant consequence of it. In giving the S more time for search, we have also given him the opportunity to make one or more saccades and thereby to show the limit of his initial fixation and fast search.

Two further questions arise. Why were the median latencies for lasting exposure longer for some S's than the latencies for brief exposure? The S operated under an instruction for speed in both experiments. Presumably because the latencies for lasting exposure contain an admixture of cases in which the S interrupted the first fast search with a saccade and a second fast search. The process was thus less efficient than it might have been. The second question: Where are these critical elements that the S finds in larger matrices, the matrices containing more elements than the CN? Presumably in the outer part of the initial sub-matrix. One must remember that, under the condition of brief exposures, the S missed completely many of the critical elements: more and more of them as the relative radial distance of the critical element from center increased.

Mrs. Eddy and Miss Coonley repeated this experiment with Miss Stanley's method, and two groups of 4 S's each; they obtained substantially the same results. Nevertheless, a much more developed method would be required to solve with certainty the problems mentioned above. The method would require

a faster shutter, for a more certain control of exposure time. The exposure time would presumably be held constant for a given S, and thus would not be allowed to depend upon response-time. The response-method would be an improved one. The presentations would be completely randomized, rather than appearing in blocks. Certain positions of the critical element would be the <u>same</u> in matrices of different areas, so that the speed of finding them could be systematically compared under various conditions. Finally, if at all possible, the eye-movements of the S should be monitored during the exposure and response.

IV. Results: the Effects of Stimulus Variation

A. The Type of Discrimination Employed.

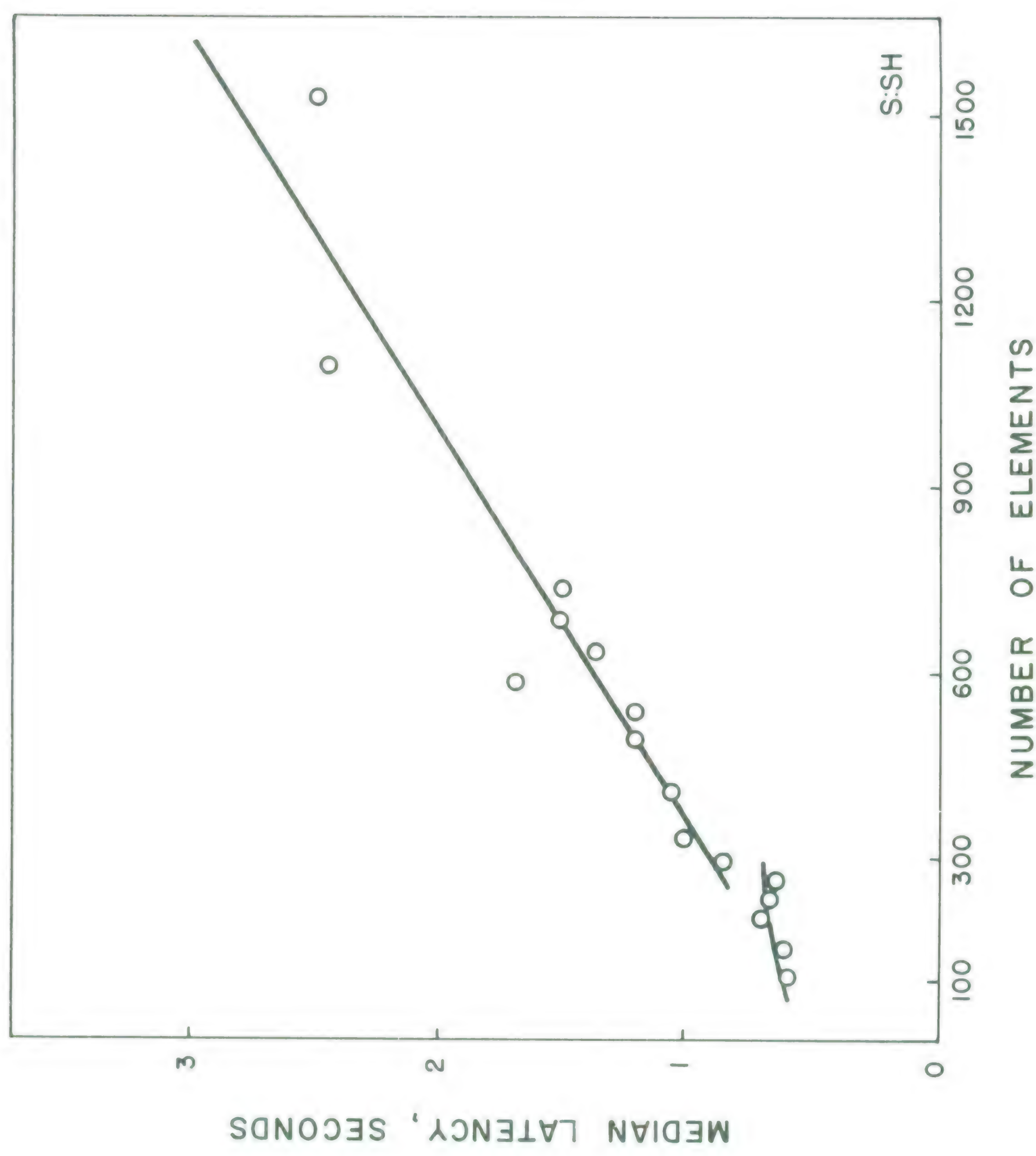
So far we have been concerned with the process of fast search in one discrimination: a form-discrimination, the finding of a triangle in matrices otherwise composed of circles. A size-discrimination was treated only incidentally in the preceding section. Can we find evidence of the CN and the inferred process of fast search in other discriminations? If so, how big is the CN for these discriminations?

The principal evidence comes from Miss Carter's thesis and the early form of the method of lasting exposure described above in the sections on methodology. Frequently the full range of square arrays was not employed in these experiments, but where possible, intermediate values of number-of-elements were inserted to permit a finer determination of the CN. The number of observations is relatively small, yet the location of the CN was never much in doubt.

The first experiment to be described dealt with a color-discimination: the S searched for a red solid circular element in matrices otherwise composed of green solid circular elements of the same size. The dimensions of the elements and of the matrix pattern were the same as those for the first experiments that dealt with form-discrimination. The colors were produced by typing the matrix with colored ribbon. This entailed some difficulties: the two colors could be matched only very roughly for brightness, and the typing of the red critical symbol was not always uniform. Yet the characteristic small discontinuities appeared in the plots for all 3 S's; Fig. 16 shows the plot for one S on arithmetic coordinates. The CN's for the three S's are 225-256; 256-289; 225-256. These are higher than the corresponding CN's for the form-discrimination. Again there is an indication of stable individual differences. We see only a restricted part of the upper branch of the function; that part can be approximated with a straight line of fairly steep slope.

Fig. 16

Showing for one S(SH) the median latency in secs. as a function of the number of elements in the matrix for all numbers of elements. Search for a red circle in matrices otherwise composed of green circles. Arithmetic coordinates. 40 observations per point. (After Carter).


S:SH
MEDIAN LATENCY, SECONDS
0
1
2
3
NUMBER OF ELEMENTS
100
300
600
900
1200
1500

Miss Carter's next evidence concerns size discrimination. The S searched for a large solid black circle in a matrix otherwise composed of small solid black circles. The diameter of the circles, as presented on the screen, were 0.53 in. for the small circles and 0.81 in. for the large circle. The matrices were square, and typed with IBM materials, as before.

Fig. 17 presents the data for one S; the results for the other 4 S's are very similar. Even with a rather close spacing of points, the transition appears as a first-order discontinuity; perhaps with an even closer spacing (if that were possible) it would appear sigmoid. The two branches can be approximated with straight lines of low slope. The upper branch would presumably turn upward at still larger values of number-of-elements than those used by Miss Carter.

The values of the CN are much larger than those encountered so far: for the 5 S's, 2916-3249; 2304-2601; 1444-1521; 1369-1444; 729-900. These values are a long way from the liminal values of a range-of-attention experiment, and we must again point out how little is demanded of the S in this experimental situation: only the approximate location of a circle that was larger than the rest.

The discrimination of the large circle is thus apparently "easy"; the large circle must stand out like a sore thumb even in a matrix of 700-3200 small circles. Miss Carter studied another easy discrimination. The stimulus sheets were very simply prepared by omitting one of the circles in an otherwise complete matrix of small black solid circles. The S searched for the blank space in the matrix. A typical curve appears in Fig. 18. It is much like the curve for size discrimination in Fig. 17. The values of the CN are again high: 1681-1764; 1600-1681; 1369-1521; 1296-1521; 729-900. The individual differences are again obvious.

It is plain that the process of fast search can deal with large number of elements, providing that the requirements for the discrimination are sufficiently reduced. There are two more main points to be made, concerning matrix area and the size of stimulus differences, respectively.

Fig. 17

Showing for one S(DD) the median latency in secs. as a function of the number of elements in the matrix, for all numbers of elements. Search for a large black circle in a matrix otherwise composed of small black circles. Arithmetic coordinates. 10 observations per point. (After Carter).

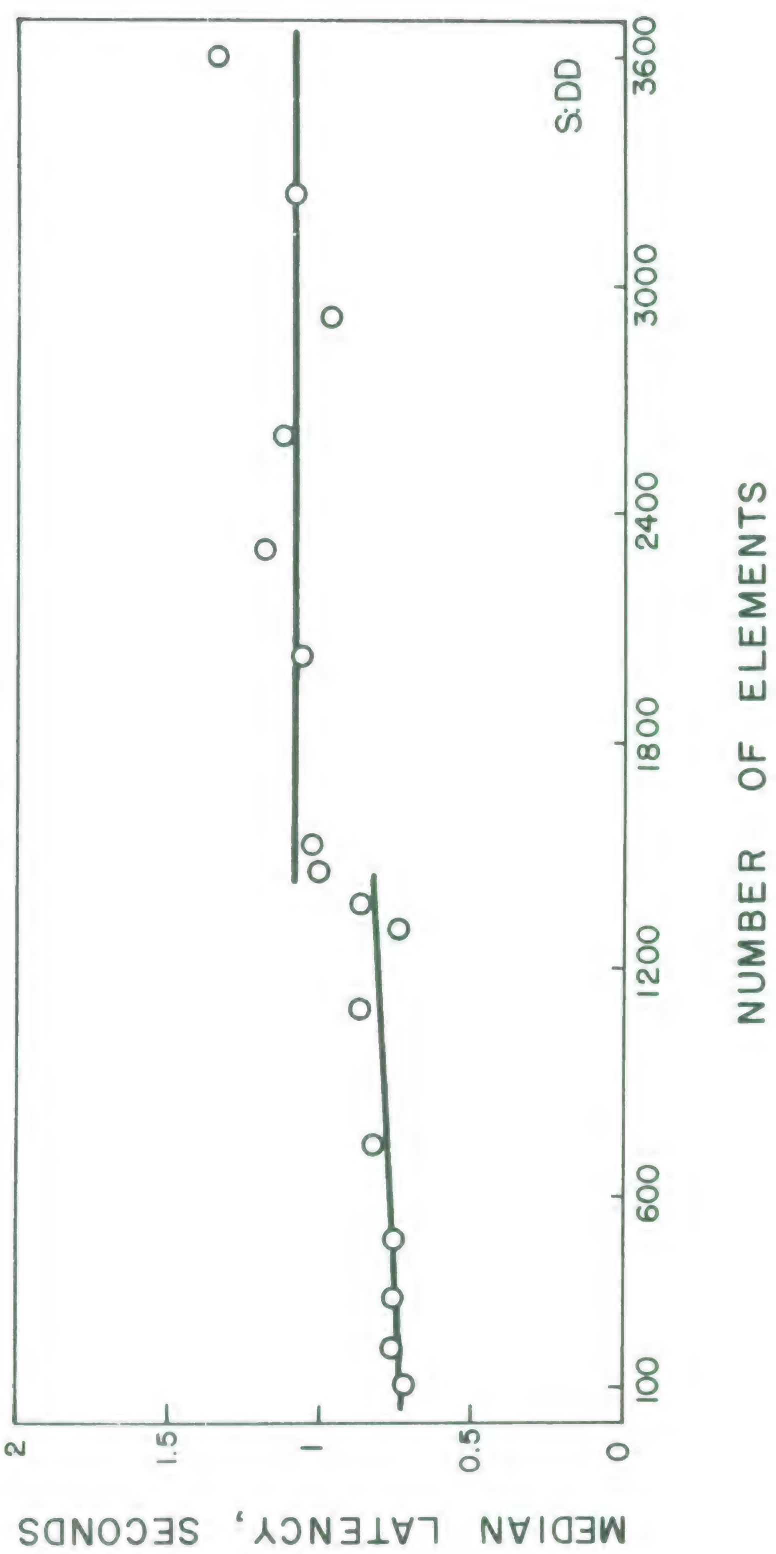
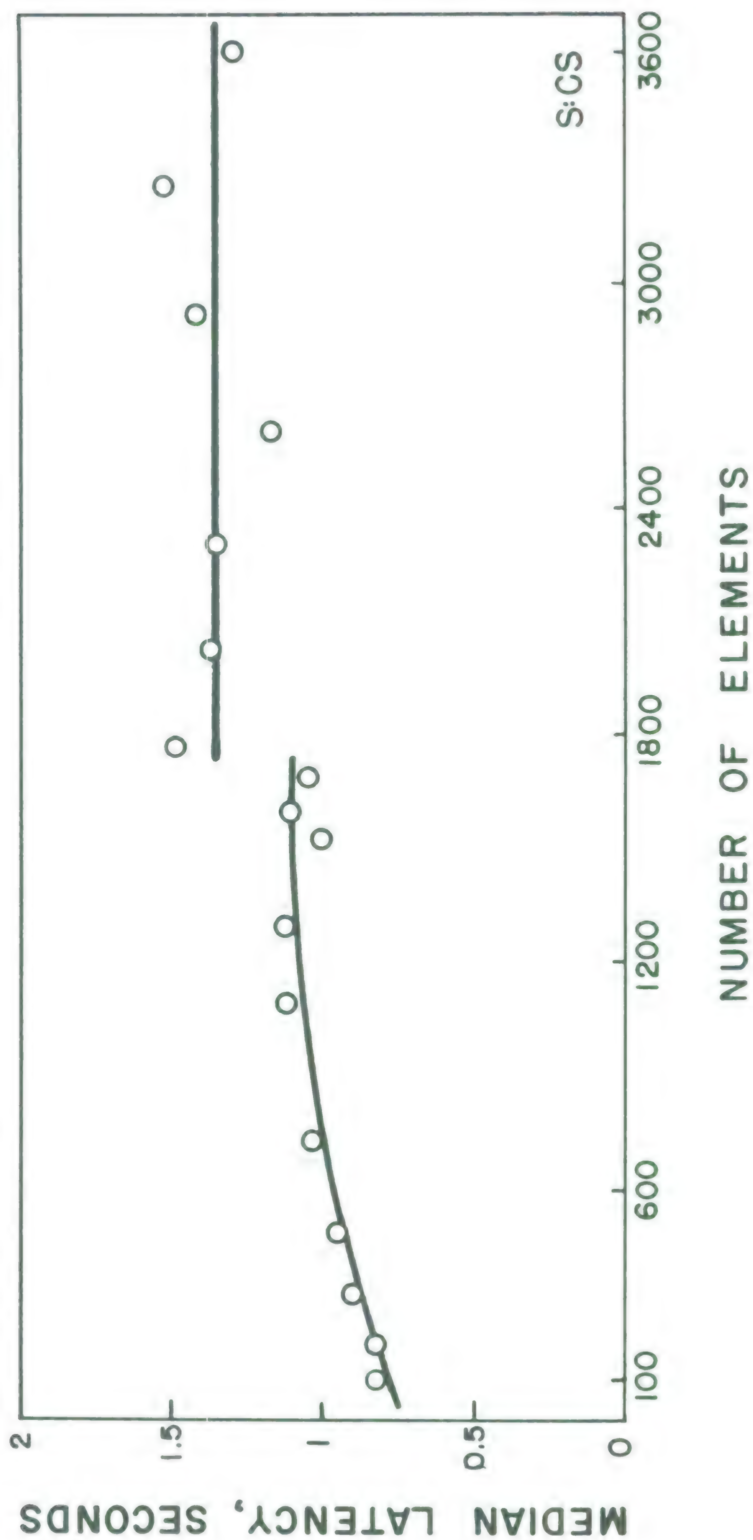

S:DD
MEDIAN LATENCY, SECONDS
0
0.5
1
1.5
2
NUMBER OF ELEMENTS
100
600
1200
1800
2400
3000
3600

Fig. 18

Showing for one S(CS) the median latency in secs. as a function of the number of elements in the matrix, for all numbers of elements. Search for a blank space (circle omitted) in a matrix of small black circles. Arithmetic coordinates. 10-20 observations per point. (After Carter).


MEDIAN LATENCY, SECONDS
0
0.5
1
1.5
2
NUMBER OF ELEMENTS
100
600
1200
1800
2400
3000
3600
S:CS

Matrix area and the number of elements were confounded in most of our experimental designs. One consequence of this is that we cannot tell whether the number or the area is the limiting variable reflected in the CN. Another consequence is more interesting: if the CN is large, we may be sure that the fast search has covered a large area as well as a large number of elements. This is true of the size and the blank-space discriminations cited above, for example. So we know that the area of fast search may be relatively large and that it varies with the particular discrimination required of the S. This ought to be held in mind when, at some later date, a model is selected for the fast-search process. It is no wonder that attention has proved to be a difficult area of experimental psychology, when this is just one of its many complications.

The next inference runs parallel to the one just drawn. Both the number of elements and the area covered in fast search vary with the stimulus difference between the critical element and the other elements. Evidence for this statement comes from a comparison of Miss Carter's and Miss Stanley's results for size discrimination. Miss Carter used a stimulus difference of 0.28 in. (of circle-diameter, as projected); Miss Stanley a difference of 0.14 in. The central or median stimulus values were nearly the same: 0.67 and 0.64 in. respectively. Miss Carter found large CN's, 729-900 to 2916-3249. Miss Stanley found relatively small ones: 100-121 to 225-256, corresponding to her smaller stimulus difference. Even though the methods of the two experiments were somewhat different, we may note that the two ranges of CN's do not overlap. A variation in number and area with stimulus difference has been observed incidentally in a much later experiment, outside the scope of this report.

B. The Shape and Pattern of the Array

It is quite natural to ask whether a CN would be found at all in irregular stimulus arrays. Conceivably the CN could depend on some regularity of external shape such as squareness, or of internal pattern, such as the rows and columns of a matrix. These are relatively simple questions, but it was not until the end of the contract work that Miss Coonley and Mrs. Eddy answered them, employing the familiar form discrimination of triangle-in-circles.

They prepared typed stimulus arrays of three different kinds:

Irregular outside-regular inside.

The external contour of the arrays was blob-shaped. The internal pattern consisted of regular rows and columns, like a rectangular matrix.

Regular outside-irregular inside.

The external contour of the arrays was square. The internal regularity of rows and columns was thoroughly broken up.

Irregular outside-irregular inside.

The external contour was blob-shaped, the internal regularity was thoroughly broken up. Ten stimulus values were used for each kind of array. They consisted of 25-529 elements.

Fortunately, the results are quite definite. An irregular external contour interferes in no way with finding a CN, although quite conceivably a deeply invaginated contour might do so. The condition to consider is irregular outside, regular inside. The plots for all 5 S's showed very clear transitions. The data of two of the S's appear in Figs. 19 and 20. One could not wish for more convincing evidence of a transition.

The result might be taken to mean that the region of fast search has no specific shape, and that it can conform to any blob-shaped matrix. This is not the only possible interpretation and there is evidence contrary to it in later sections; we must think of the region of fast search as having at least an approximate shape.

An irregular inside pattern may obscure the CN somewhat, although it does not

Fig. 19

Showing for one S(Gr) the median latency in secs. as a function of the number of elements in the array. The external shape of the array was irregular; the internal pattern, regular. Medians for the central locations of the critical element and for all locations of it are plotted separately. Arithmetic coordinates. 20 observations per point for central locations; 120 for all locations.

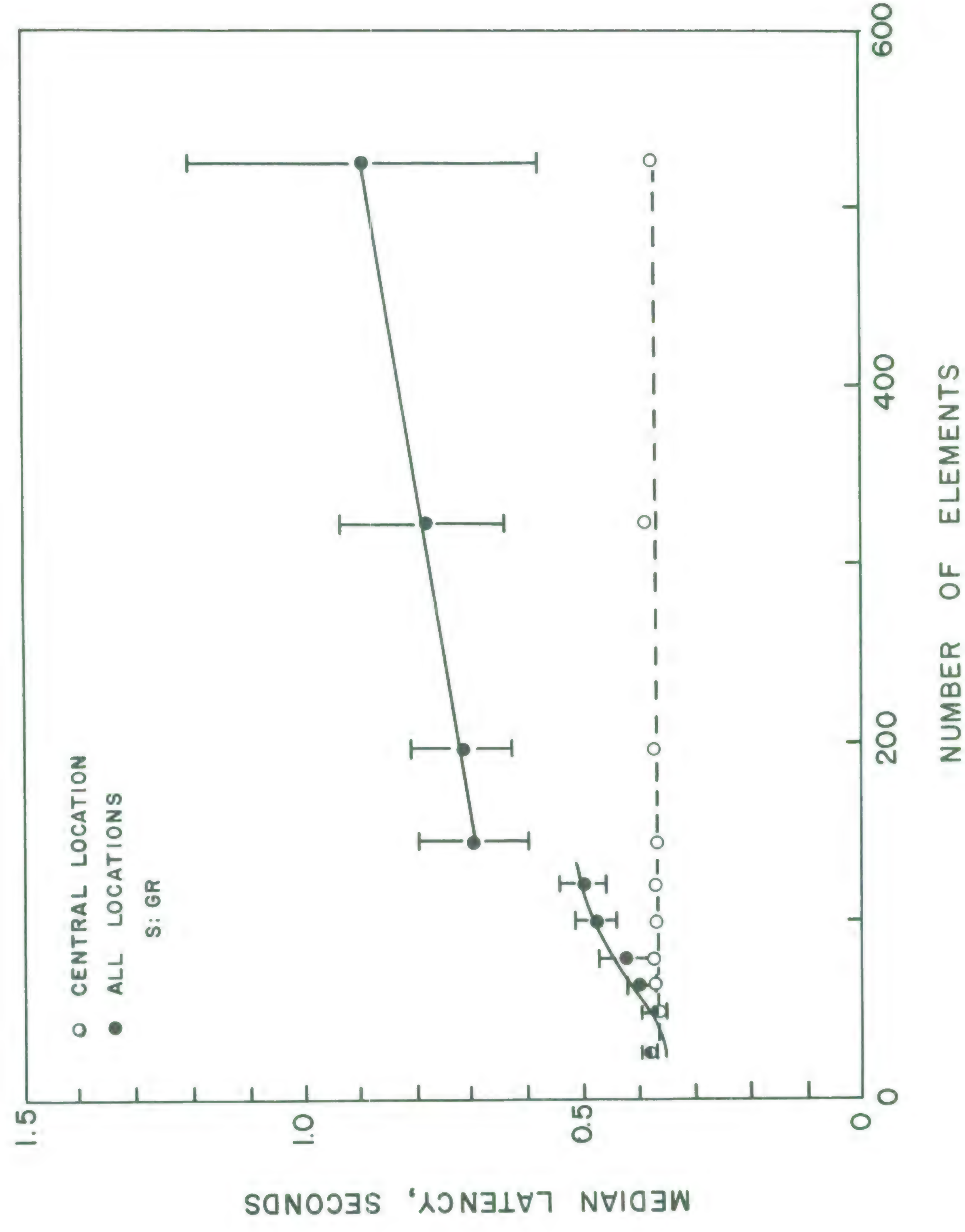
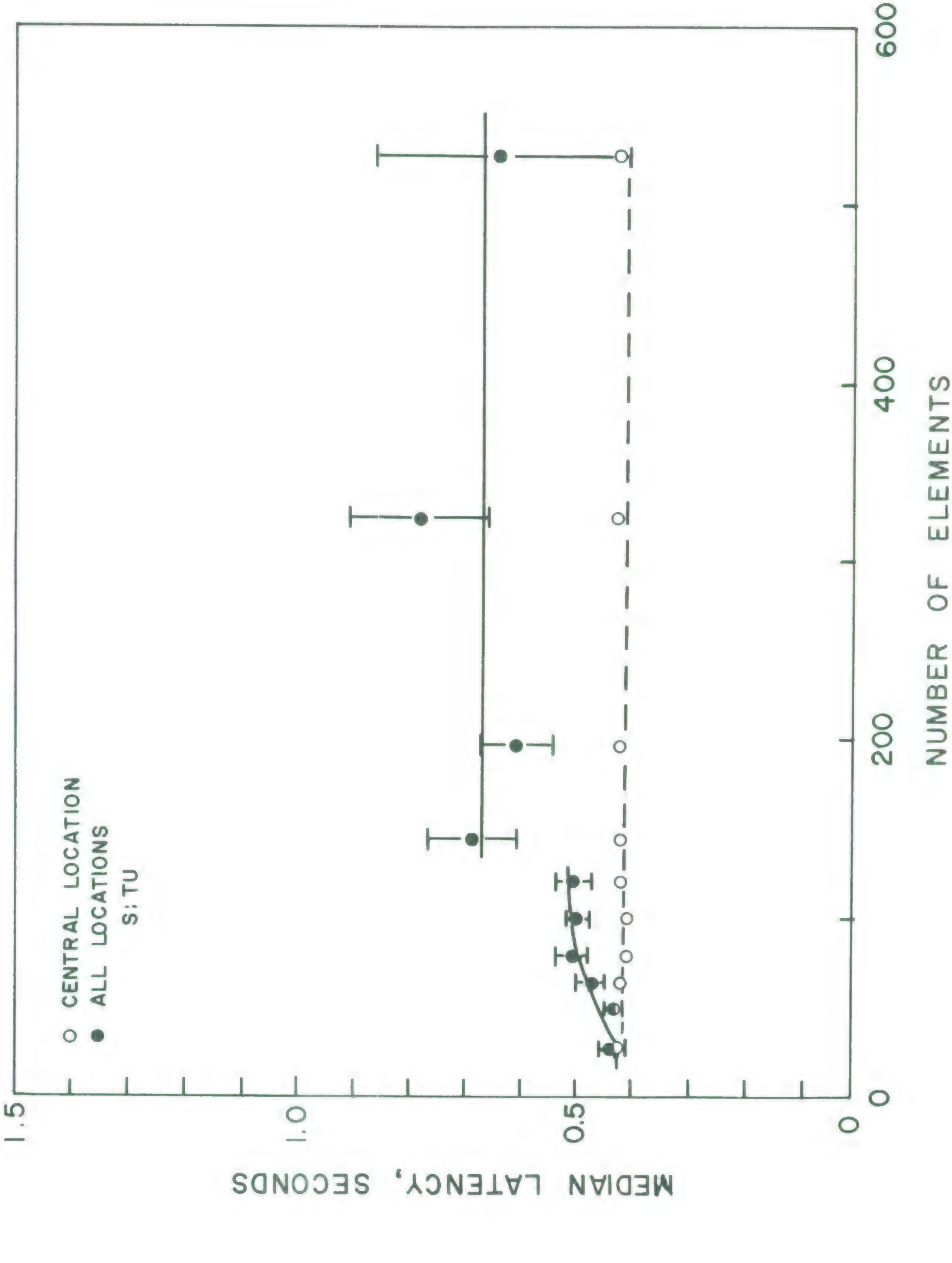

CENTRAL LOCATION
ALL LOCATIONS
S: GR
MEDIAN LATENCY, SECONDS
1.5
1.0
0.5
0
NUMBER OF ELEMENTS
0
200
400
600

Fig. 20

Showing for one S(Tu) the median latency in secs. as a function of the number of elements in the array. The external shape of the array was irregular; the internal pattern, regular. Medians for the central locations of the critical element and for all locations of it are plotted separately. Arithmetic coordinates. 20 observations per point for central locations; 120 for all locations.



CENTRAL LOCATION
ALL LOCATIONS
S: TU
MEDIAN LATENCY, SECONDS
NUMBER OF ELEMENTS
0
0.5
1.0
1.5
200
400
600

always do so. One can imagine arrays with large gaps that would almost certainly obscure the transition. With the condition regular outside - irregular inside and 5 S's, two of the transitions were rated very clear, two fairly clear, and one obscure. Fig. 21 is an example of a transition rated fairly clear.

Results from the condition irregular outside - irregular inside support the inferences drawn so far: the outside contour does not obscure the transition, and the inside pattern may do so. The 5 transitions were rated as follows: one very clear, three clear, one fairly clear. Fig. 22 shows an example of a transition rated as clear.

To summarize: variations in the external contour do not obscure the CN. This finding is consistent with the idea of the initial sub-matrix: **this** is the region in which fast search is taking place. As long as the region is not invaded, the external contour of the array should indeed have no effect. As regards the internal pattern: the CN does not depend on a regular matrix pattern, although irregularity may obscure the transition which locates the CN.

Fig. 21

Showing for one S(Sc) the median latency in secs. as a function of the number of elements in the array. The external shape is regular (square), the internal pattern is irregular. Medians for the central location of the critical element and for all locations of it are plotted separately. Arithmetic coordinates. 20 observations per point for central locations; 120 for all locations.

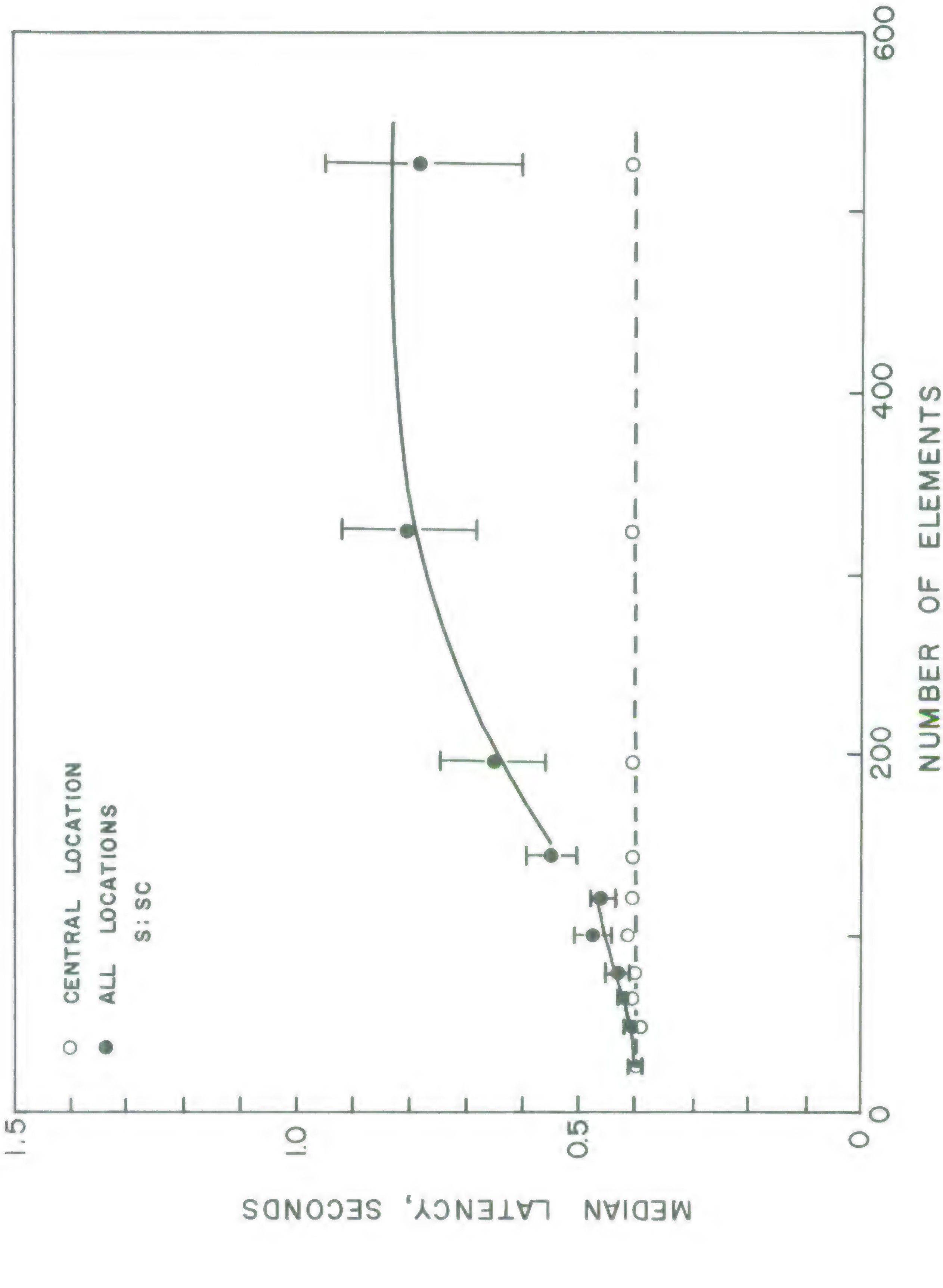
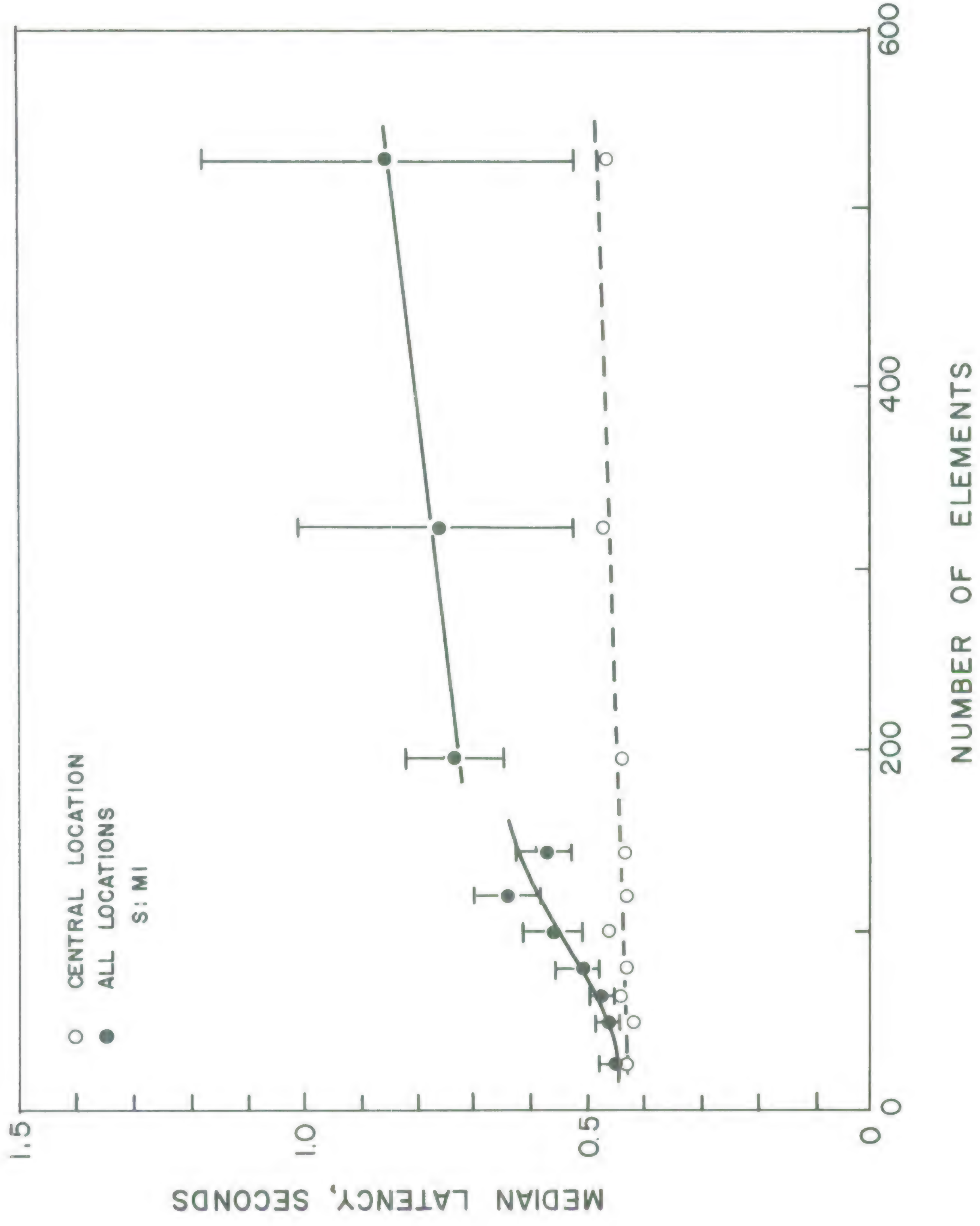

CENTRAL LOCATION
ALL LOCATIONS
S: SC
MEDIAN LATENCY, SECONDS
1.5
1.0
0.5
0
0
200
400
600
NUMBER OF ELEMENTS

Fig. 22

Showing for one S(Mi) the median latency in secs. as a function of the number of elements in the array. The external shape of the array is irregular; the internal pattern, also irregular. Medians for the central location of the critical element and for all locations of it are plotted separately. 20 observations per point for central locations; 120 for all locations.


CENTRAL LOCATION
ALL LOCATIONS
S: MI
MEDIAN LATENCY, SECONDS
0
0.5
1.0
1.5
NUMBER OF ELEMENTS
0
200
400
600

Near the end of the contract work, we were inclining to the belief that the area of fast search might have at least an approximate shape. To obtain some evidence, Mrs. Eddy and Miss Coonley conducted a carefully planned experiment to determine the CN with certain variations of external shape. The two basic shapes were the square and rectangle; the width of the rectangle was between 1/3 and 1/4 of its length. In addition, the orientation of the rectangular array varied in 4 steps: vertical, horizontal, diagonal with the top tilted toward the right, diagonal with the top tilted toward the left. For each shape and orientation there were 10-11 areas and corresponding numbers of elements. The smallest number of elements was 12 or 16 (2 x 6 and 4 x 4 respectively). The largest number was 418 (11 x 38) for the diagonal arrays; 529 (23 x 23) for the squares; 900 (15 x 60) for the vertical and horizontal arrays. There was complete concurrent randomization of number-of-elements and shapes. The arrays of elements were internally regular, arranged in horizontal rows and vertical columns no matter what the external orientation of the array. Mrs. Eddy and Miss Coonley employed the familiar discrimination of triangle-in-circles, typed matrices of constant density, the improved experimental method, and 6 female S's of college age. The number of observations was relatively large: 120 per number-of-elements per shape per S. This adds up to 46,080 observations in this one experiment alone.

The values of the CN for each shape and each S appear in Table I. With certain interesting exceptions noted in the table and discussed below, values of the CN could be readily located throughout. This confirms the finding of the preceding experiment, that variations in external shape do not preclude finding a CN.

Nevertheless, the preceding experiment did not show that the <u>value</u> of the CN is independent of external shape. We might be able to find shapes that favor a relatively large CN, and others that favor a relatively small one. More specifically, let us imagine for the sake of simplicity that the region of fast search is circular. A superposed, circumscribed square matrix would (by definition)

Table I. Showing for each of the 6 S's and for each of the 4 shaped matrices the values of the critical number (CN)

S:	Gr	Tu	Sc	Pe	Fi	Mi
Vertical Bar	double CN: 24-40 and 70-108	70	70	70-108	70	double CN: 24-40 and 70-108
Horizontal Bar	70	108-171	40-70	double CN: 40-70 and 108-171	108-171	40-70
Diagonal Right	75-85	75-85	85-132	75-85	75	75-85
Diagonal Left	48	48-60	60-75	48	48	48-60
Square	81-100	81	100	100	144-196	81-100

include the circle exhaustively. This corresponds to a relatively large value of the CN. But if we squeeze out this circumscribed square matrix to a rectangular matrix of the same area, not all of the circle is covered by the rectangle no matter how we shift or tilt it. This corresponds to a decreased value of the CN.

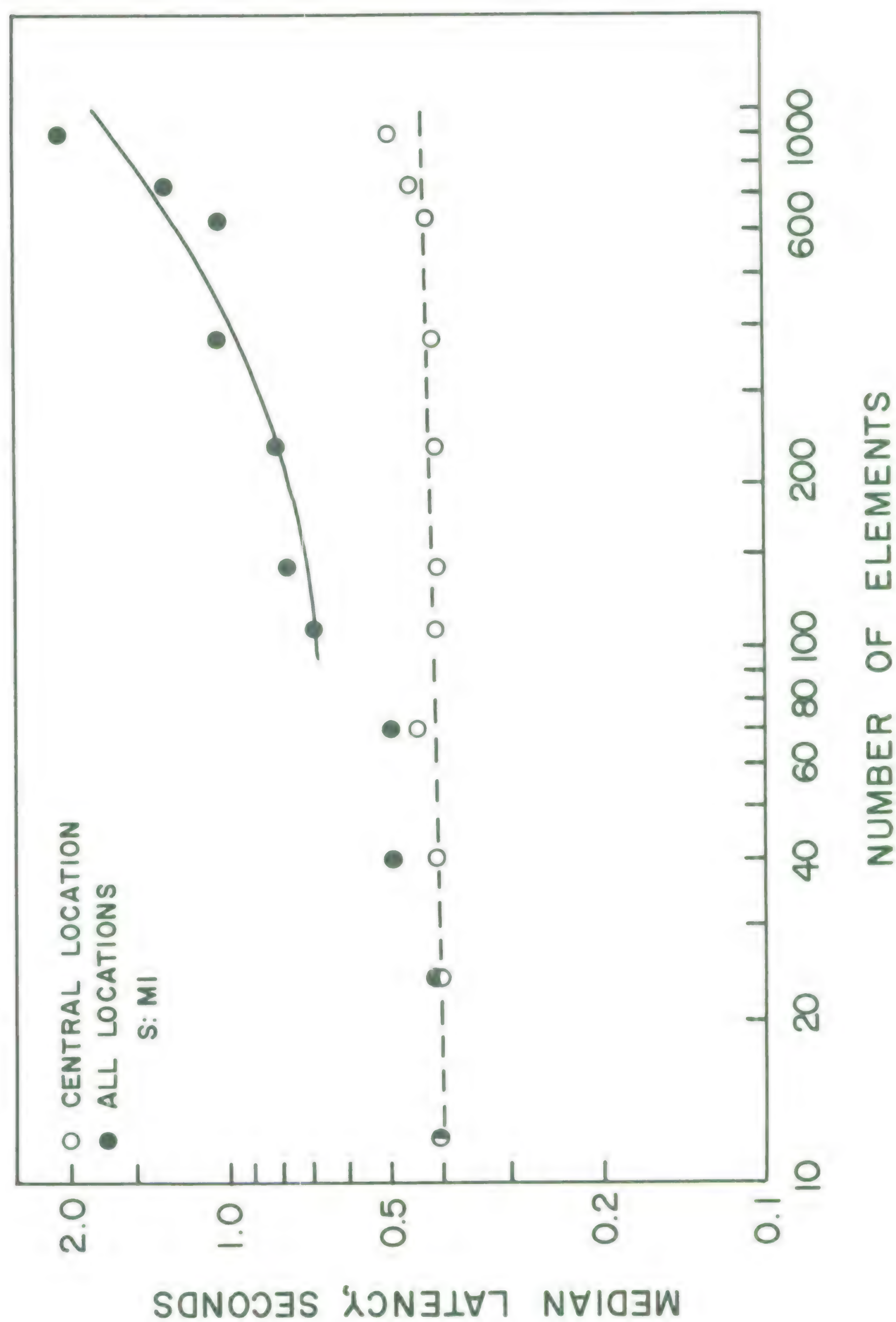
Let us examine Table I from this point of view, and omit the values labelled "double CN" as special cases, to be discussed below. We see that for 5 out of 6 S's, the values of CN for square matrices are indeed larger than those for the rectangular matrices of any orientation. The one exception, the horizontal rectangle for S: Tu, may also be a double CN, but we cannot be sure of it. The implication of the finding is that the region of fast search has at least an approximate shape, and the shape is something like a circle, square or thick oval. Apart from the comparison with square matrices, we may note from Table I that the CN for diagonal left is smaller than that for diagonal right (all 6 S's). The comparison of horizontal rectangles with vertical ones is obscured by the special cases of the double CN.

Fig. 23 shows one of the special cases. In order to show the problem, no curves have been drawn to some of the points in the figure. One cannot tell whether the CN is located at 24-40 or 70-108; alternatively,there could be two transitions and two CN's. Our previous experiments had sometimes shown a little of this difficulty; now, with relatively thin rectangular matrices, the difficulty is more severe. Yet the double CN is still the exception rather than the rule, as the table makes plain.

How to explain the double CN? Presumably in the terms already employed. When the matrix is a relatively thin horizontal rectangle, for example, some S's will very frequently make a saccadic scanning movement before the information from the initial fixation is exhausted. This scanning behavior is a relatively strong operant, and the horizontal stimulus pattern triggers it off prematurely. This produces the first possible transition in the graph. If the critical element is not located, there follow a second saccade or more saccades, thus producing the second possible transition and the second branch of the function. Only a good photographic method could check this interpretation.

Fig. 23

Showing for one S(Mi) the median latency in secs. as a function of the number of elements in the array. The external shape of the array is a vertically oriented rectangular bar; the internal pattern is regular. Medians for the central location of the critical element and for all locations of it are plotted separately. Logarithmic coordinates. 20 observations per point for central locations; 120 for all locations.



CENTRAL LOCATION
ALL LOCATIONS
S: MI
MEDIAN LATENCY, SECONDS
2.0
1.0
0.5
0.2
0.1
NUMBER OF ELEMENTS
10
20
40
60
80
100
200
600
1000

V. Results: The Shape of the Field of Search

A. A Preliminary Spatial Analysis

It occurred to us that the results of the preceding experiment, as given in Table I, might give another indication of the shape of the region of fast search. Knowing the CN for a horizontal orientation of a rectangular array, we could determine the length of the stimulus array lying just under the CN, or at its lower limit. This length was taken as the length of the horizontal axis of the field of fast search for the particular S. A strip of paper was cut with a length proportional to this axial length. Similar strips were cut for the other orientations: vertical, and the two diagonals. Then we superposed the strips, each in its proper orientation, and looked to see what shape the resulting figure might have.

There were several serious difficulties with this essentially graphical method. The instances of a double CN made trouble. The strips all passed through a common "fixation-point", but there was no way of telling how much of the strip should lie on one side of the common point and how much on the other. In spite of these difficulties, we gained the impression that the indicated shape was a somewhat deformed circle or oval.

B. Mapping a Field of Short-Time Visual Search

It now became plain that a whole new experimental approach was required, with the special aim of tracing out the shape of the field of fast search. The method of lasting exposure, as used so far, had yielded only indirect evidence concerning shape. Perhaps a true tachistoscopic method would do better. It also offered the possibility of taking measurements independent of latency and of the inference of a CN; such methological independence is always welcome. At the same time, it was necessary to avoid the limits of short-time memory as before, and to make the stimulus-conditions at least

roughly comparable to those of the foregoing experiments.

Dr. Corbin and the author built a projection tachistoscope to permit a fairly close control of exposure times, and Miss Chaikin prepared her matrix material photographically as a still-film for projection. The photographic method was much like that described in an earlier report from our laboratory.[11] The type of discrimination, stimulus dimensions and viewing distance are all the same as those used in most of our experiments. The dependent variable was the frequency of positive judgment rather than latency; a series of limens determined the shape of the field of search. The apparatus, method, and results are described in Miss Chaikin's thesis, and in the resulting brief publication in Science.[12,13] That publication is No. ESD-TDR 62-215 of the Operations Application Laboratory; it should also be regarded as an integral part of the present report.

The results may be itemized as follows:

1. The shape revealed by the liminal contours is most frequently ovaloid, with flattened sides. There are frequent irregularities in the contours. The long axis of the ovaloid is the horizontal one.

2. There is more of the field of search above the fixation point than below it. Right-left asymmetry also occurred, but was not prominent.

3. The field of search expands as a function of exposure time.

With the use of true tachistoscopic exposures, we are entering a field already rich in experimental evidence. For some of that evidence, see the article by H.S. Terrace.[14] For still more, and particularly for the evidence developed in the work of Project Michigan, see the monograph by Harcum.[15] There is also a group of experiments by Harcum and his collaborators, done subsequent to the work at Project Michigan; see, for example, Camp and Harcum, 1964.[16] It is not possible to review all of this work here. Much of it is relevant, but there are two features that distinguish our methods

from those of many experimenters; the methods might therefore be expected to yield different results. First, we have intentionally used non-verbal materials, to avoid the intrusion of reading-behavior. Secondly, by not requiring the reproduction of stimulus materials we have avoided the limits of short-term memory.

There are some pieces of evidence from our laboratory that fall outside this report, because they came from a later project. Yet our purpose is to inform the Air Force, not to mystify it; accordingly, two points follow that relate to the results of Miss Chaikin's experiment listed above:

1. A recent experiment using the method of lasting exposure, axial rows of elements, and a decreased density of elements has produced fields of search approximately circular and centered on the fixation point. Viewing was binocular, as in our other experiments. The measure depended upon latencies, and so could not be a liminal one.

2. The expansion of the field with exposure time is most probably a Roscoe-Bunsen effect. The evidence comes from a very recent experiment parallel to Miss Chaikin's, in which the S's searched for a short straight line tilted one way from the vertical in a matrix otherwise composed of aimilar lines tilted the other way. We chose the discrimination because Leibowitz et al have shown that it is apparently not Roscoe-Bunsen controlled: in ordinary language, if you can see a line at all, you can tell quite accurately how it is tilted.[17] Our experiment suffered from an insufficient number of observations, but nevertheless showed no expansion of the field with increased exposure time.

VI. Some Remaining Problems

A. The CN represents some kind of discriminatory limit. Is it a limit of number-of-elements, independent of the area and density of the stimulus array? Miss Burke and Miss Smith, undergraduate majors in psychology, conducted an experiment to answer this question. They used square matrices, a size discrimination, and an intermediate form of the experimental method: all the same as Miss Stanley's. They varied the density of the matrix; i.e. the number of elements per unit area. The total area of the matrix varied correspondingly. We did not know at the time that the external shape of the matrix could be made rectangular as well as square, without impairing the determination of the CN. Consequently the stimulus values of number-of-elements were perfect squares and too far apart, and it was not possible to find out whether the CN had indeed changed with density.

A much more recent experiment, beyond the scope of this contract, has given a definite and interesting answer. The CN is not constant as a function of varying density. It decreases markedly at low densities. At these low densities, an <u>area</u> is constant: the area that includes the CN, at the given density. The data are still being examined, but it looks as though we should experiment intensively at the lower densities, and think in terms of a limiting area rather than a limiting number (at these densities).

B. We need to determine the relation between the CN on one hand, and the stimulus difference on the other. This is the difference between the critical element and the other elements. A size-discrimination might be suitable for this experiment. The existing, improved method should be adequate for the initial experiment, at least.

C. The idea of a limiting area, rather than a limiting number, suggests an interpretation that is quite simple, and different from the informational one proposed earlier in this report. The S fixates the center of the screen. Within some contour in his indirect vision a single triangle can be discriminated from a single circle, presented successively in the same place. Outside the contour the two are blurred and indistinguishable. The contour is determined by an acuity, i.e. the resolving power of the eyes and remaining visual system. So the argument goes thus: at low densities, the S can find in his initial fixation a critical element lying anywhere inside the limits of his acuity for these particular contrasted stimuli.

Miss Carter made some isolated observations on one S which suggested that the acuity limit for triangle vs. circle lay further out than the area corresponding to the CN. Nevertheless, the question should be reopened, and answered with the aid of special experiments in perimetry. These are not easy to arrange, because their conditions must largely duplicate the conditions of the main experiments on the CN.

D. What are the S's eyes doing, in fixation and saccadic movement, during the exposures of our stimuli? We do not know, and are only now beginning to design methods of finding out. Photography in our experimental situation has some special requirements: a wide angle (approx. 30 degrees), recording of the eye movement trace in two dimensions, simultaneous recording of the stimulus array, at least a fairly good registration of the trace on the stimulus array, some means of timing the trace. All of this will not be easily done.

Given the method or a good approximation to it, we would hope to check the absence of saccadic movements during brief exposures. During lasting

exposures, we would like to investigate the relation of the first saccade to the location of critical elements within the initial sub-matrix. As a general tool, and without using photography at all, a simplified scheme might be developed for monitoring saccades and checking central fixation. Lastly, it is conceivable that a manual or verbal response can be dispensed with entirely; we might discover from the photographs whether or not the critical element was found, and when the saccadic eye movement toward it started. This in turn might yield a more reliable measure of latency.

E. We have often drawn up frequency-distributions of the latencies in our experiments, but have made no systematic use of them. They show a large principal mode at short times, suggesting initial fast search. This type of analysis might be very useful if the latencies were somewhat more reliable, and if a photographic or other monitoring scheme were available.

VII. Conclusions

A. The early phases of visual search or "active attention" may be fruitfully investigated by requiring the S to search for a unique element in matrices otherwise composed of uniform elements. Simply by varying the total number of elements, one may cover the entire range of difficulty of search.

B. Useful methods include the improved method of lasting exposure and the method of brief exposure, as described in the text. Desirable additions and improvements include: true tachistoscopic exposure for large fields of opaque projection; photographic recording of eye-movements in the experimental situation; photographic or other automatic monitoring of fixation during exposures; improved measures of response-latency; still better ways of making stimulus arrays.

C. For some discriminations, the gross relation between the latency of the locating response and the number of elements is approximately linear. This has been found also by others.

D. A close examination of the relation shows a different shape: the latencies are mainly constant at low values of number-of-elements, and then shift to a slightly higher level in a localized transition. The transition enables one to define and state the "critical number" (CN): the value of number-of-elements at which the transition occurs.

E. The critical number reflects some discriminatory limit or limits, but these may be limits of area rather than of number.

F. An analysis of latencies from different parts of the matrix supports the hypothesis of the <u>initial sub-matrix</u>. This is a part of a larger matrix lying about the fixation-point, and containing a number of elements equal to the critical number. Still more evidence is needed to verify the hypothesis, nevertheless.

G. The critical number can be found for different types of discrimination: for form, color, size and the omission of an element. There are individual differences, but there are also approximate values of the critical number characteristic of each type of discrimination.

H. The critical numbers are far higher than the range of attention in classical experimental psychology.

I. The critical number can usually be found for stimulus arrays that are irregular in external contour and regular in internal pattern. When the internal pattern is irregular, the transition that determines the critical number may be obscured (although it need not be).

J. An experiment using rectangular bar-shaped arrays as well as square ones indicates that the field of fast search has at least an approximate shape.

K. An experiment employing form-discrimination, tachistoscopic exposures, and a liminal method indicated one characteristic shape: an ovaloid with flattened sides, lying somewhat more above the fixation point than below it.

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Attention is called to the reports of Project Michigan for other work on visual search.

Appendix A

PRODUCTION OF DOT MATRICES BY A DIAZO PROCESS

A diazo-copying process* was used to produce the dot matrices for our last few experiments. The basic idea of this method of matrix production was to print over and over again from the same master matrix, changing with each printing only the position of the one dot in the matrix which differed in shape. This triangle, in our case, was to be the object of search. This method has proven to be less time consuming, less subject to error and more economical than earlier methods in which every matrix to be shown was individually typewritten. Here is a brief account of the diazo-copying process.

First a master copy of the largest size matrix of dots was typed on very white paper in preparation for printing. This consisted of equally spaced circular black dots arranged in rows and columns. There were 56 columns and 56 rows. In addition several rows of spare circular dots and several rows of triangles were typed on the master. A cut was then produced of the master, and copies of the whole array were printed on transparent acetate sheet with pressure sensitive adhesive backing.**

The next step was to transfer the translucent sheet with its printed dots to heavier translucent mylar sheet to lend this master copy toughness and a degree of permanance for the printing operation. The rows of spare dots and triangles were cut off the Chart-Pak copy at this time and saved for the editing of copy. As noted above, each print was to have one triangle substituted for one circular dot somewhere in the matrix. This was accomplished by editing; this consisted of cutting around the dot to be removed with an Exacto knife (enough to loosen the dot-carrying film with its adhesive backing, but not enough to cut the mylar behind

* We have utilized the materials and facilities of Technifax Inc., Holyoke, Mass. We are grateful to them for their courtesy.

** The Chart-Pak Company of Leeds, Mass. was extremely helpful in producing this special run. They retain the cut of our materials for subsequent re-runs.

it). A triangle was then quickly pressed into the gap where the dot had been removed and the whole copy inspected for scratches and dot-imperfections. These were repaired by using acetate ink pens.

The copy was now ready for printing, using diazo-coated paper to produce black-on-white prints. In the work so far accomplished, this was Technifax 18-s sheet specially trimmed to fit our 11" x 11" sheets. The translucent master was placed over the diazo-coated side of the sheet, pin-registered on one marginal side, and run through a controlled exposure to ultra-violet light. Printing followed immediately by exposing the sheet to ammonia vapor bath. For best results the prints were run through the ammonia exposure twice.

The master was then re-edited on a light table. The triangle of the last printing was removed and a fresh dot substituted in its place. At another pre-determined position a dot was cut out and a fresh triangle placed in that position. All such substitutes were simply pressed home, using care to place and orient the objects in the proper matrix alignment. In our experience the same master copy was successfully used over and over to print as many as 20 different positions of the triangular object of search. In addition, for each such position of the edited triangle two printed positions could be obtained simply by turning the master transparency over and printing the obverse of the original. If research designs permitted, as many as four positions of the object of search could be obtained from the same edited master by turning the master into all 4 possible top-bottom, right-left positions. Between printing it was desirable to repair scratched dots and assure the location of those elements that had been shifted back and forth, triangle to dot, in earlier printings. The scratches on the mylar caused by knife cuts made the mylar less transparent in those locations, but by selecting proper exposure times such blemishes were "burned out" and left no printed replica. Once a master was no longer usable, a new one was ready in the form of a fresh sheet of dots mounted on heavy mylar.

Appendix A (cont.)

Finally the master copies of the matrix were altered for some experiments to vary the size, shape, and density of the matrices. Size was a simple matter of cutting the original down with scissors before mounting it on mylar. Shape was handled in the same way. Density was reduced by cutting loose whole rows and columns of dots and pulling them off the master copy. Printing then followed as described earlier.

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13. ABSTRACT

The aim of these experiments was to study the process of visual search in its early phases. Individual human subjects searched in a projected matrix of elements for one element unlike the rest; e.g., for a triangle in a matrix otherwise composed of circles. In the method of lasting exposure, the matrix was exposed until the subject responded, and the dependent variable was the latency of the response. In the method of brief exposure, the exposure time was limited, and the dependent variables were the percentage of positive responses and the latency of the positive responses. ("Positive response" means that the subject found the desired element). Among the independent variables (or classes of them) in various experiments were the following: the total number of elements in the matrix; the type of discrimination (form, area, color); the external form and internal pattern of the stimulus array. In analyzing the results of a typical experiment, the median latency is plotted as a function of the number of elements in the stimulus array.

The graph begins at nearly zero slope, and usually shows a small discontinuity or a sigmoid transition leading to slightly higher latencies. This triangle locates the critical number (CN): the number of elements at which it occurs. The critical number varies considerable with the type of discrimination required, and with the stimulus difference between the critical and background elements. It can be determined for arrays that are irregular in external contour or internal pattern.

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Abstract (1473) (Cont'd)

The critical number represents some discriminatory limit or limits; it may be a limit of area rather than of number. In dealing with large matrices, the subject apparently searches rapidly in a region around the fixation point (the initial sub-matrix). By definition, this has an area equal to that covered by the critical number in the matrix. The interpretation of the critical number and the initial sub-matrix is partly in terms of saccadic eye movements, though none have been photographed as yet.

The region of fast search may have at least an approximate shape. One experiment, using the method of brief exposures, indicated the shape to be ovaloid, with most of its area lying above the fixation point.